US009358590B2

(12) **United States Patent**
Koenig et al.

(10) **Patent No.: US 9,358,590 B2**
(45) **Date of Patent: Jun. 7, 2016**

(54) **ELECTROADHESIVE SURFACE CLEANER**

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(73) Assignee: **SRI International**, Menlo Park, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 429 days.

(21) Appl. No.: **13/915,094**

(22) Filed: **Jun. 11, 2013**

(65) **Prior Publication Data**

US 2013/0276826 A1 Oct. 24, 2013

Related U.S. Application Data

(63) Continuation-in-part of application No. PCT/US2012/030454, filed on Mar. 23, 2012.

(60) Provisional application No. 61/731,185, filed on Nov. 29, 2012, provisional application No. 61/658,335, filed on Jun. 11, 2012, provisional application No. 61/466,907, filed on Mar. 23, 2011.

(51) **Int. Cl.**
A47L 13/40 (2006.01)
B08B 6/00 (2006.01)

(52) **U.S. Cl.**
CPC .. ***B08B 6/00*** (2013.01); ***A47L 13/40*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,536,528 A 10/1970 De Geest
3,684,575 A 8/1972 King

(Continued)

FOREIGN PATENT DOCUMENTS

BE 901726 A1 5/1985
DE 202005019251 U1 3/2006

(Continued)

OTHER PUBLICATIONS

International Search Report and Written Opinion for International Application No. PCT/US2012/030454, mailed Oct. 29, 2012, 9 pages.

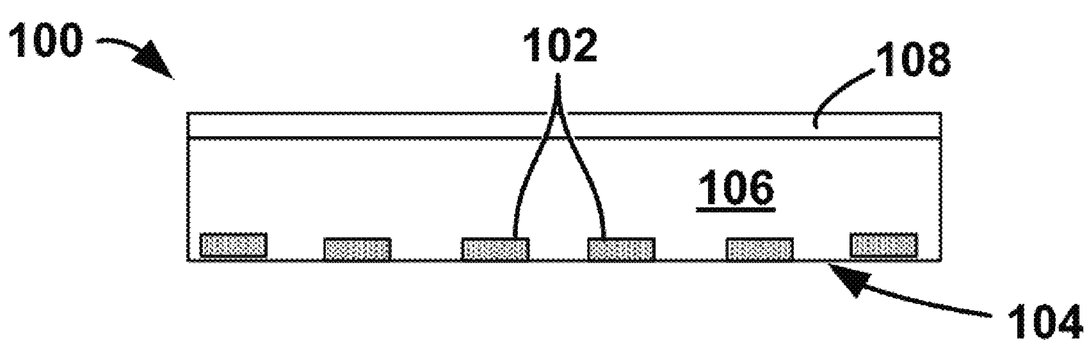
(Continued)

Primary Examiner — Eric Golightly
(74) *Attorney, Agent, or Firm* — McDonnell Boehnen Hulbert & Berghoff LLP

(57) **ABSTRACT**

An electroadhesive cleaning device or system includes electrode(s) that produce electroadhesive forces from an input voltage to adhere debris against an electroadhesive surface, from which the debris is removed when the forces are controllably modified. Controlling the input voltage may designate the size of debris to be cleaned. A power source provides the input voltage, and the electroadhesive surface can be a continuous track across one or more rollers to move the device across a dirty foreign surface. Electrodes can be arranged in an interdigitated pattern having differing pitches that can be actuated selectively to clean debris of different sizes. Sensors can detect the amount of debris adhered to the electroadhesive surface, and reversed polarity pulses can help repel items away from the electroadhesive surface in a controlled manner.

23 Claims, 26 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

4,317,661	A *	3/1982	Sasaoka	B03C 3/12 361/231
4,962,727	A	10/1990	Harada	
4,996,078	A	2/1991	Langowski	
5,229,170	A	7/1993	Narusawa	
5,378,954	A	1/1995	Higuchi et al.	
6,799,350	B1	10/2004	Gordon	
7,551,419	B2	6/2009	Pelrine et al.	
7,554,787	B2	6/2009	Pelrine et al.	
7,782,591	B2	8/2010	Cho et al.	
9,186,709	B2	11/2015	Prahlad et al.	
2004/0163667	A1	8/2004	Learman	
2005/0059239	A1	3/2005	Goto	
2005/0126260	A1 *	6/2005	Totoki	B01D 49/00 73/31.02
2007/0186522	A1 *	8/2007	Hato	A47L 9/1666 55/467
2008/0089002	A1	4/2008	Pelrine et al.	
2010/0154821	A1	6/2010	Moriya et al.	
2010/0218467	A1 *	9/2010	Witter	B01D 45/12 55/337
2010/0307342	A1	12/2010	Gibis et al.	
2012/0061903	A1	3/2012	Eguchi et al.	
2013/0276826	A1	10/2013	Koenig et al.	
2014/0064905	A1	3/2014	Prahlad et al.	
2014/0104744	A1	4/2014	Prahlad et al.	
2014/0133062	A1	5/2014	Prahlad et al.	

FOREIGN PATENT DOCUMENTS

DE	102008008576	A1	8/2009	
EP	0401489		12/1990	
EP	1852192	A2	7/2007	
EP	1974644	A2	10/2008	
EP	1985432		10/2008	
JP	S61-71433	U	5/1986	
JP	H5-285084	A	2/1993	
JP	9-90751		4/1997	
JP	H9-131290	A	5/1997	
JP	11-056731		3/1999	
JP	2001-269301		10/2001	
JP	2003-225625	A	8/2003	
JP	2009-226310	A	10/2009	
JP	2012-056745		3/2012	
KR	2010-0025814		3/2010	
WO	2005/117679	A1	12/2005	
WO	2007/143662	A2	12/2007	
WO	WO 2008070201	A2 *	6/2008	H02N 13/00
WO	2009/100744	A1	8/2009	
WO	2012/129541	A2	9/2012	

OTHER PUBLICATIONS

International Search Report and Written Opinion for International Application No. PCT/US/2013/045200, mailed Oct. 2, 2013, 8 pages.

Notification of Reason(s) for Rejection, Japanese Patent Application No. 2014-501289, dated Nov. 20, 2014.

European Search Report, European Patent Application No. 12761130, dated Sep. 9, 2014.

* cited by examiner

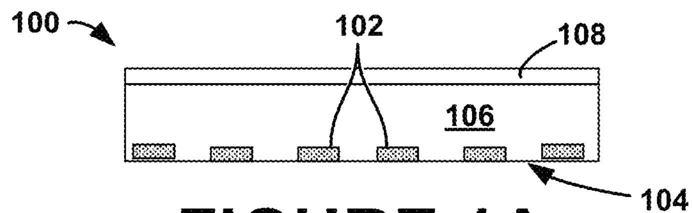


FIGURE 1A

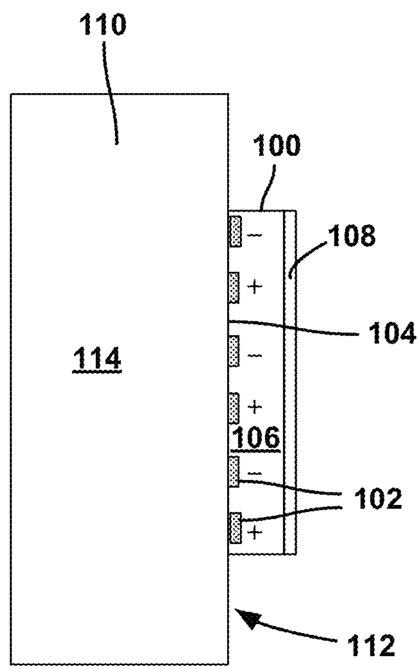


FIGURE 1B

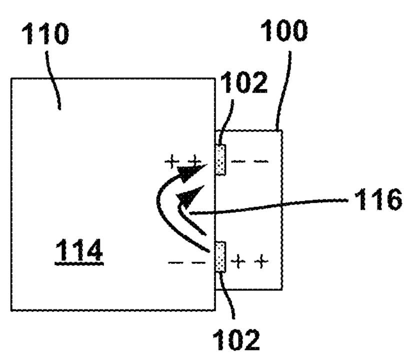


FIGURE 1C

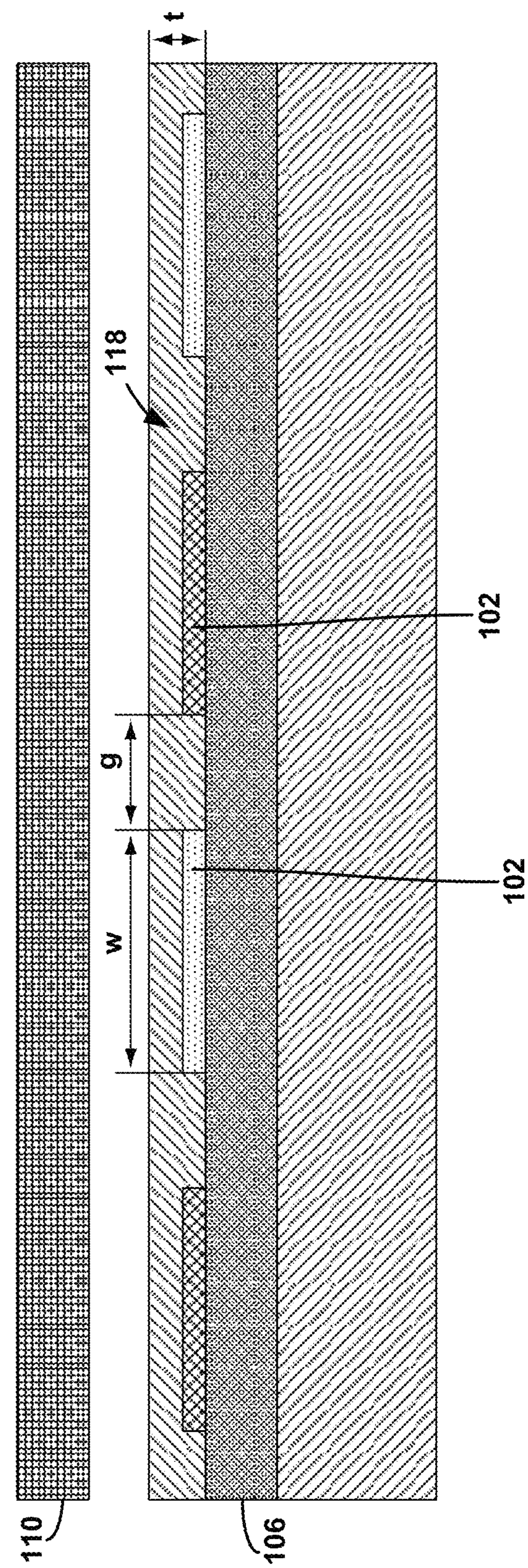


FIGURE 1D

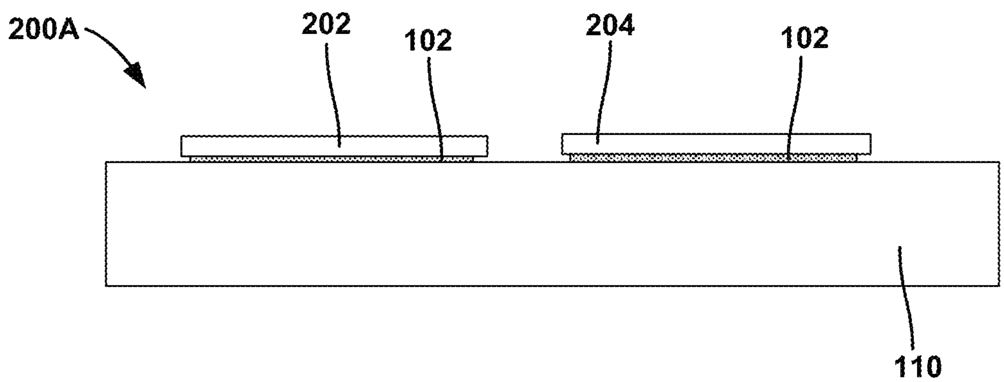


FIGURE 2A

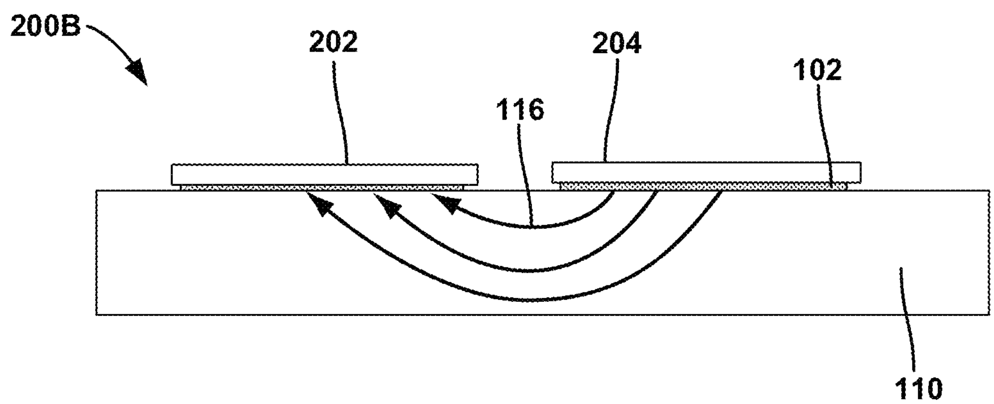


FIGURE 2B

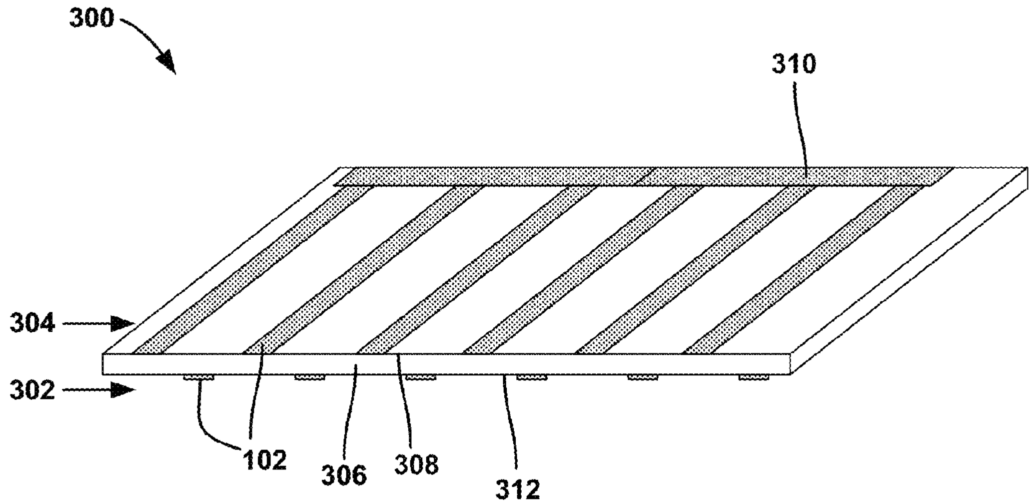


FIGURE 3A

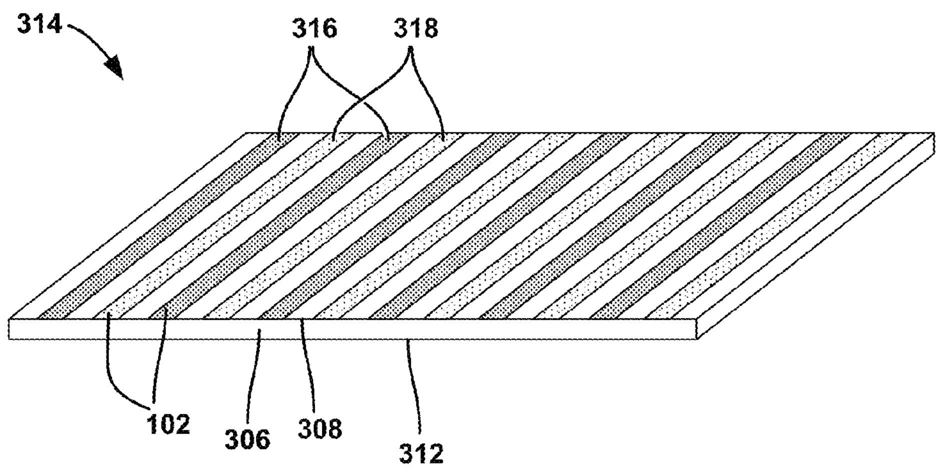


FIGURE 3B

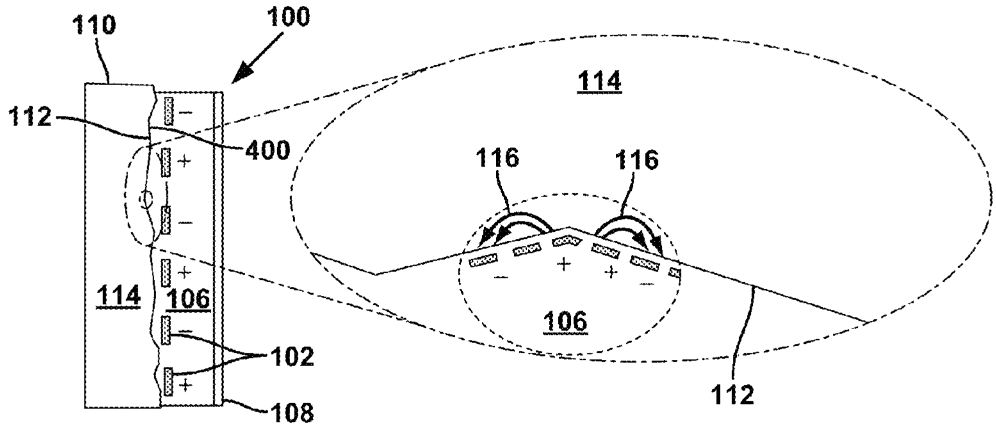


FIGURE 4A

400

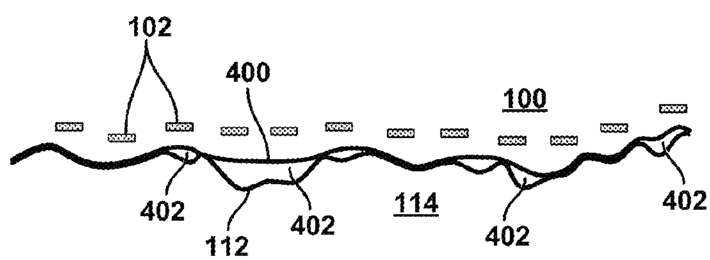


FIGURE 4B

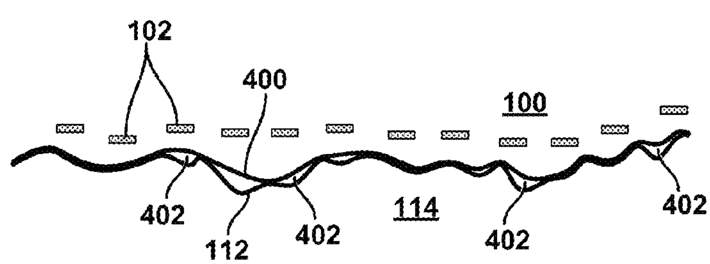


FIGURE 4C

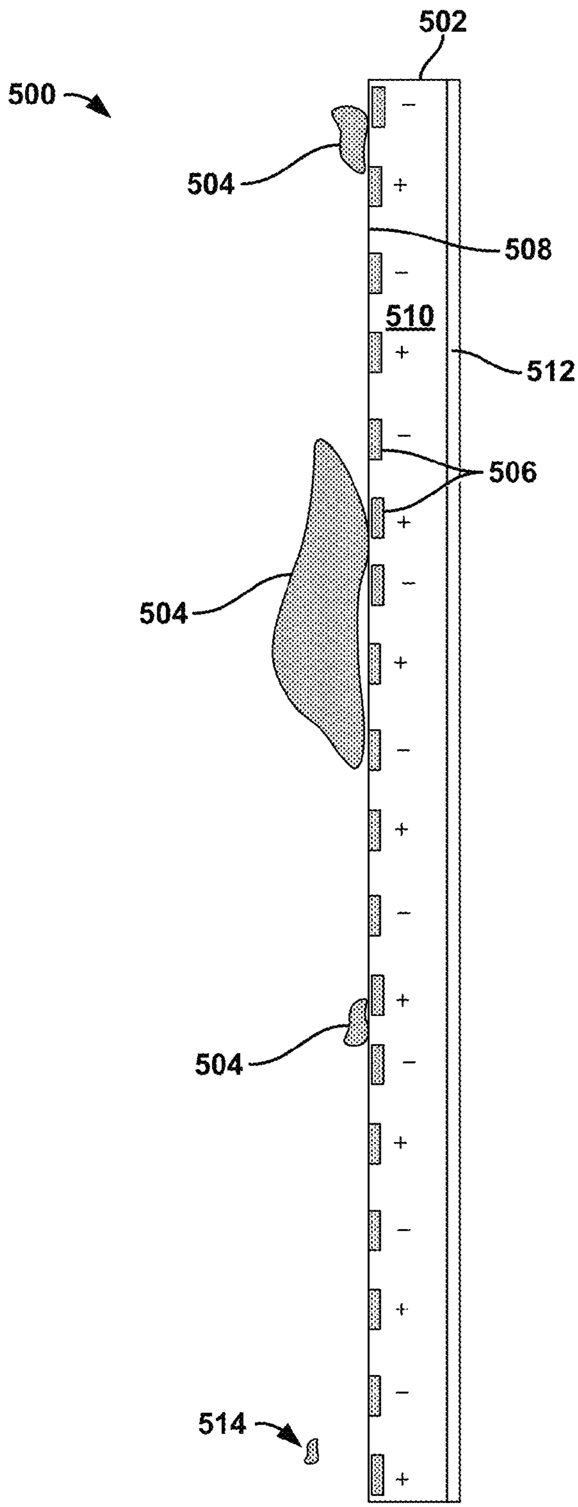


FIGURE 5

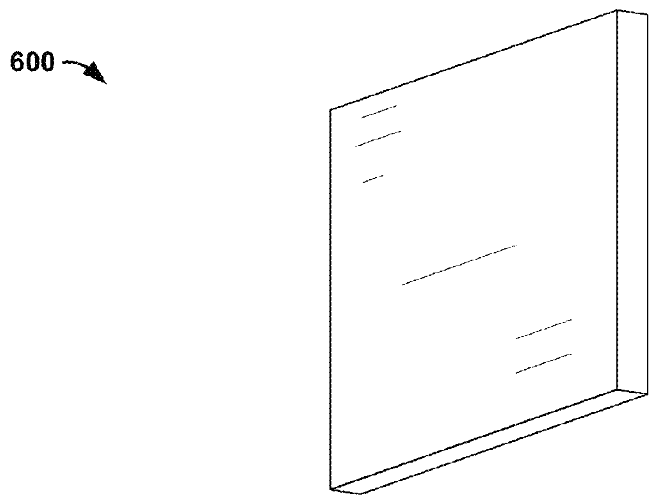
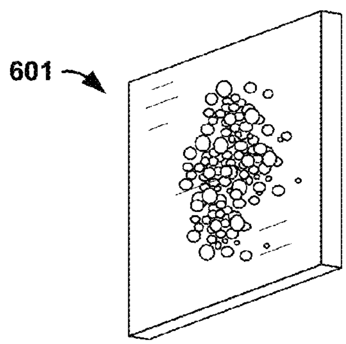


FIGURE 6A



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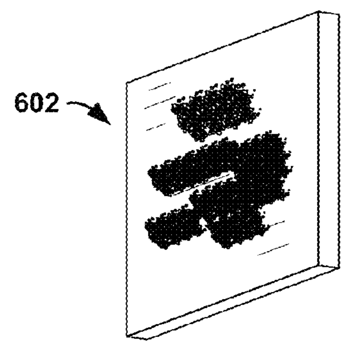


FIGURE 6C

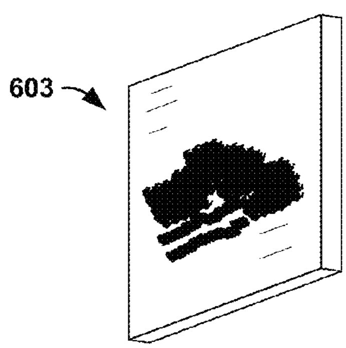


FIGURE 6D

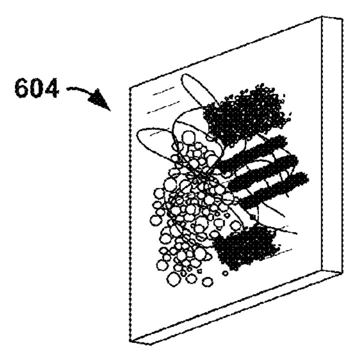


FIGURE 6E

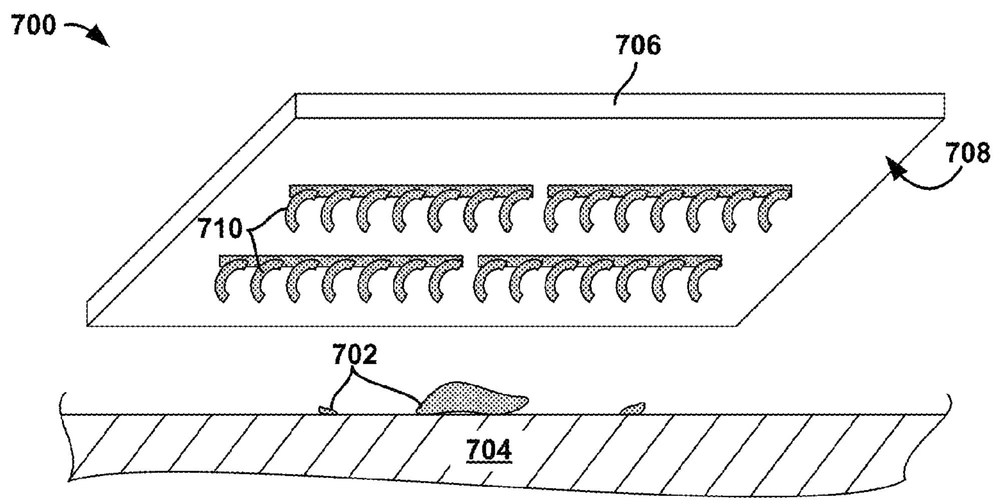
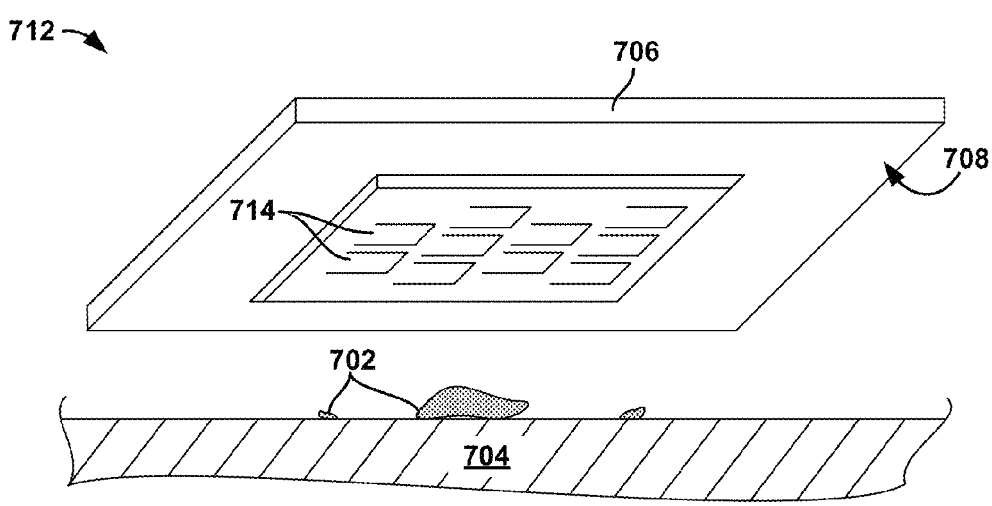


FIGURE 7A



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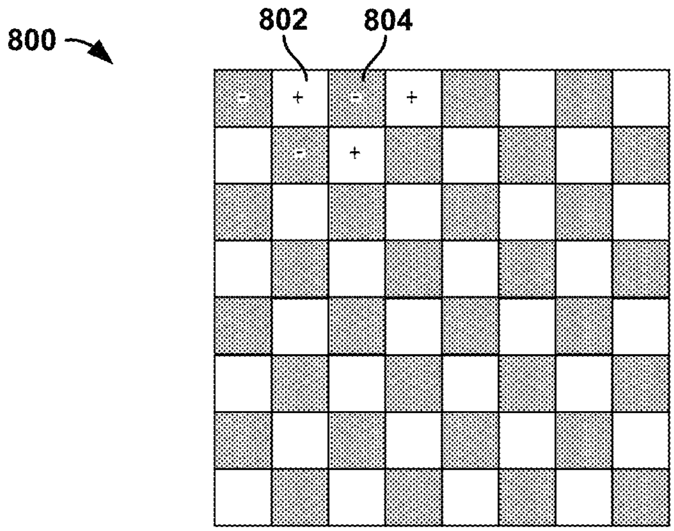

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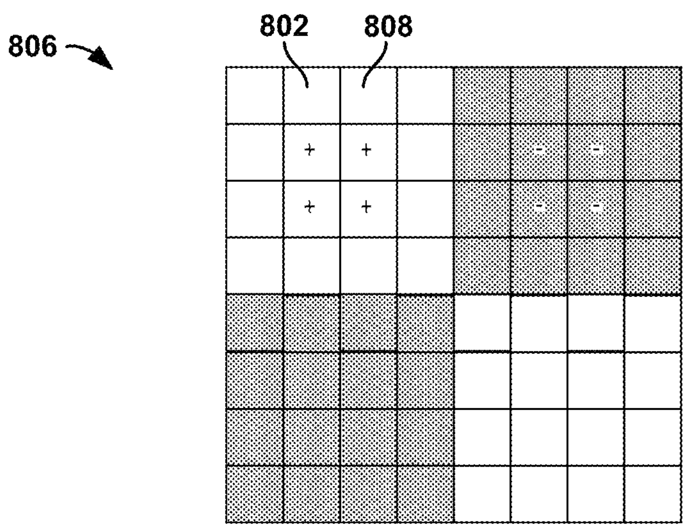

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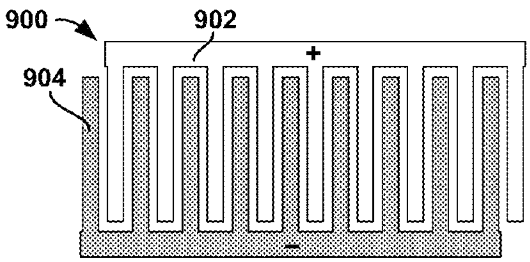
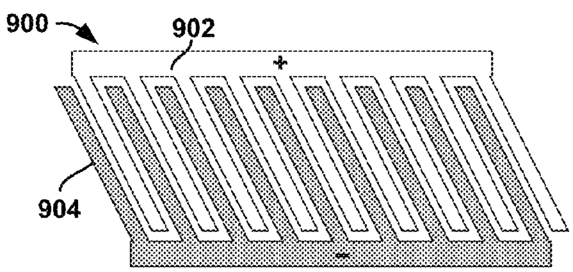


FIGURE 9A



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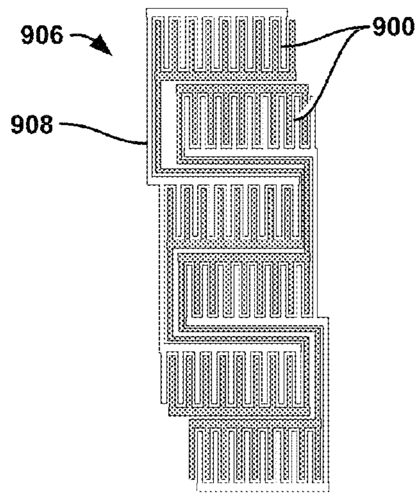

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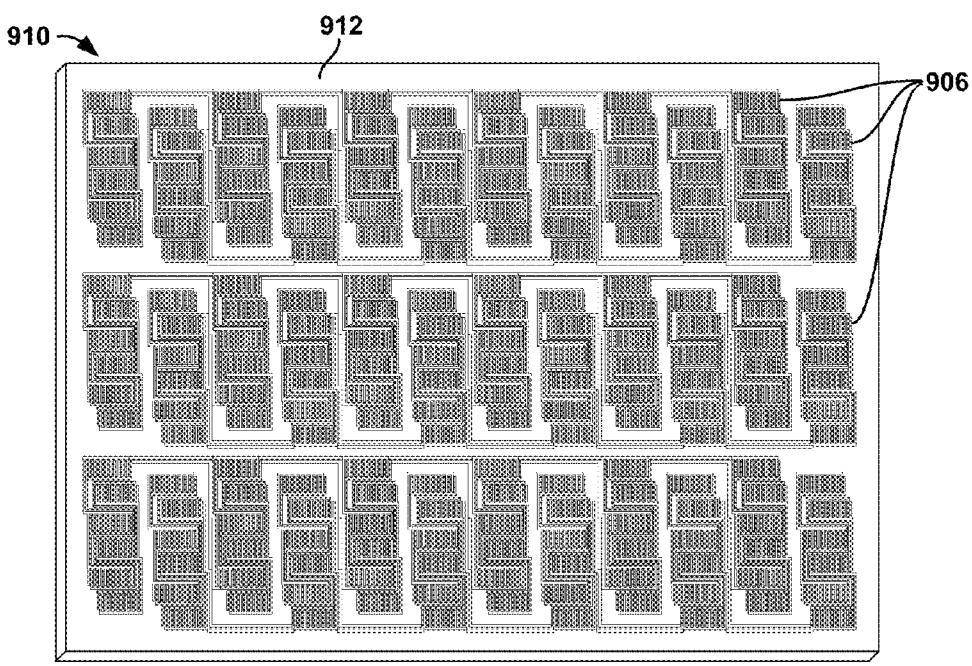

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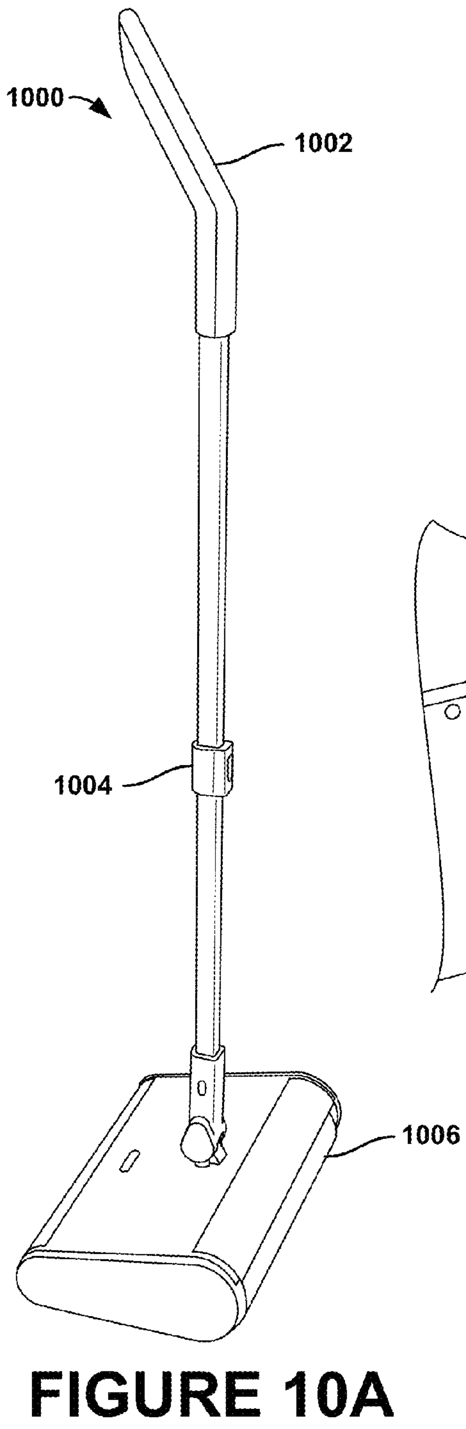


FIGURE 10A

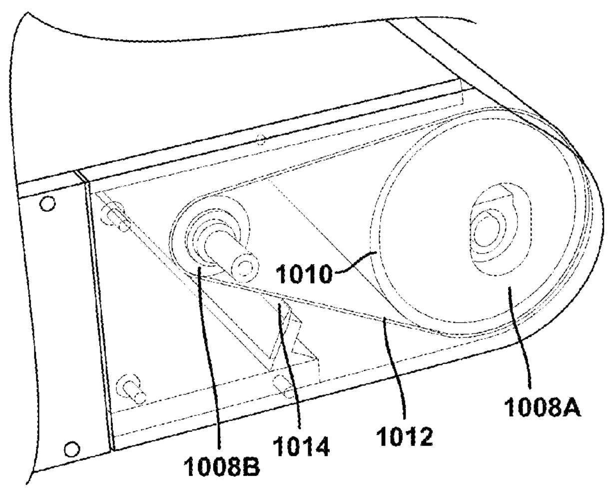


FIGURE 10B

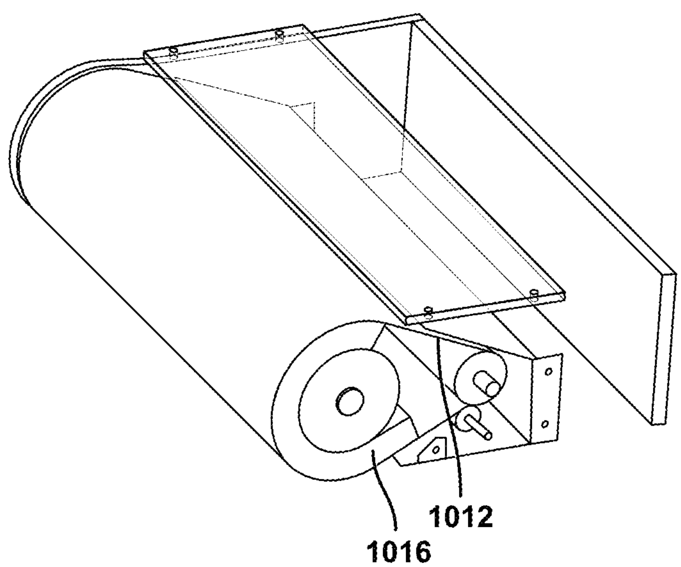
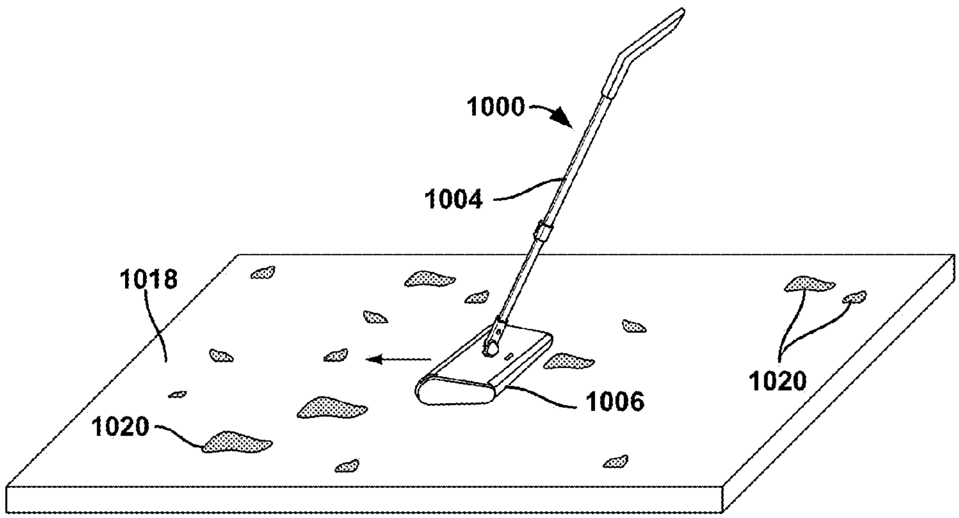


FIGURE 10C



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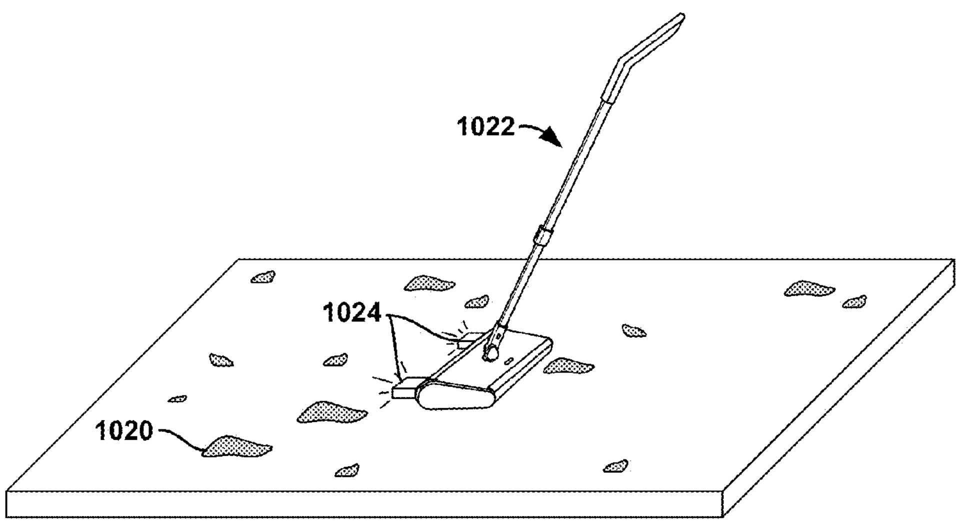

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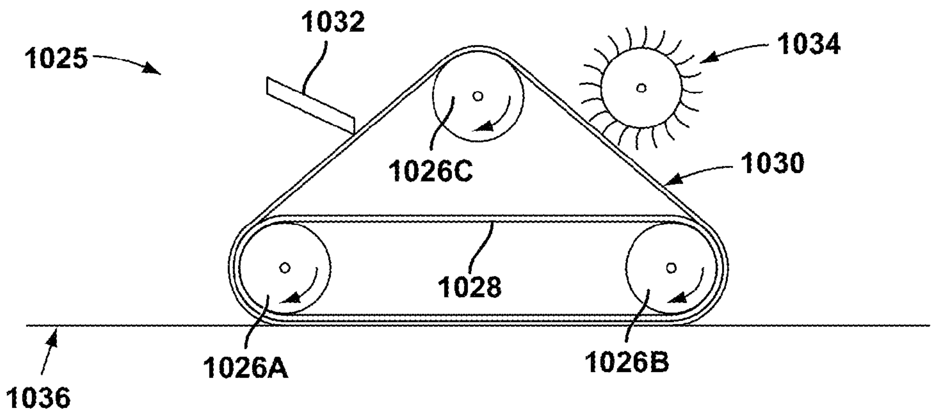


FIGURE 10F

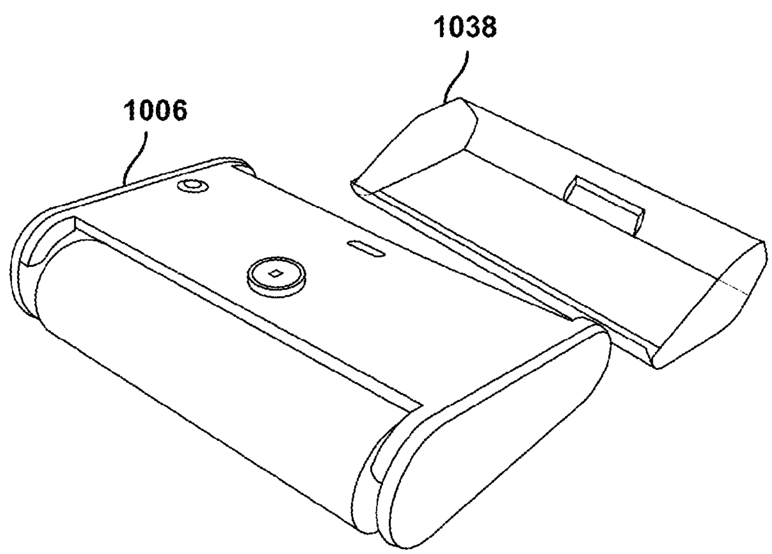
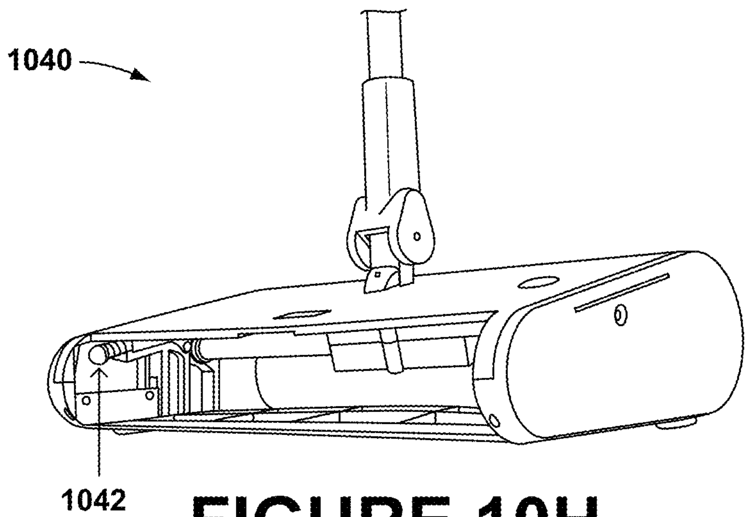


FIGURE 10G



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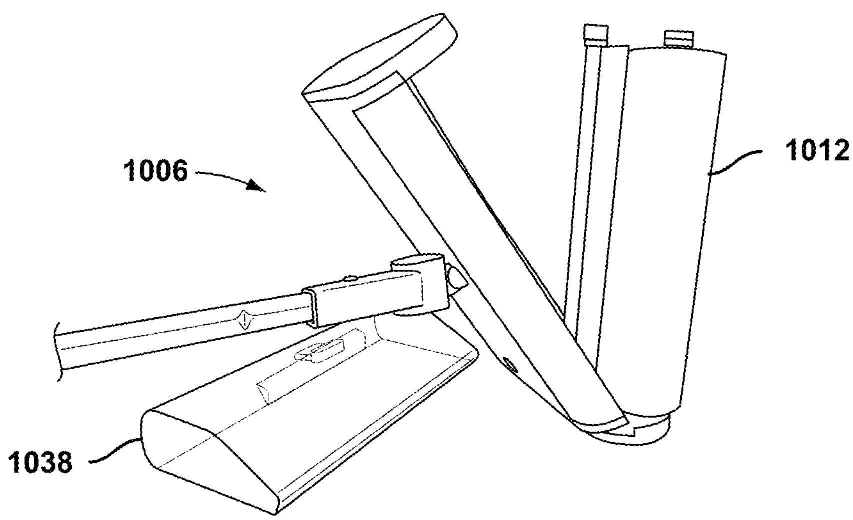

FIGURE 10I

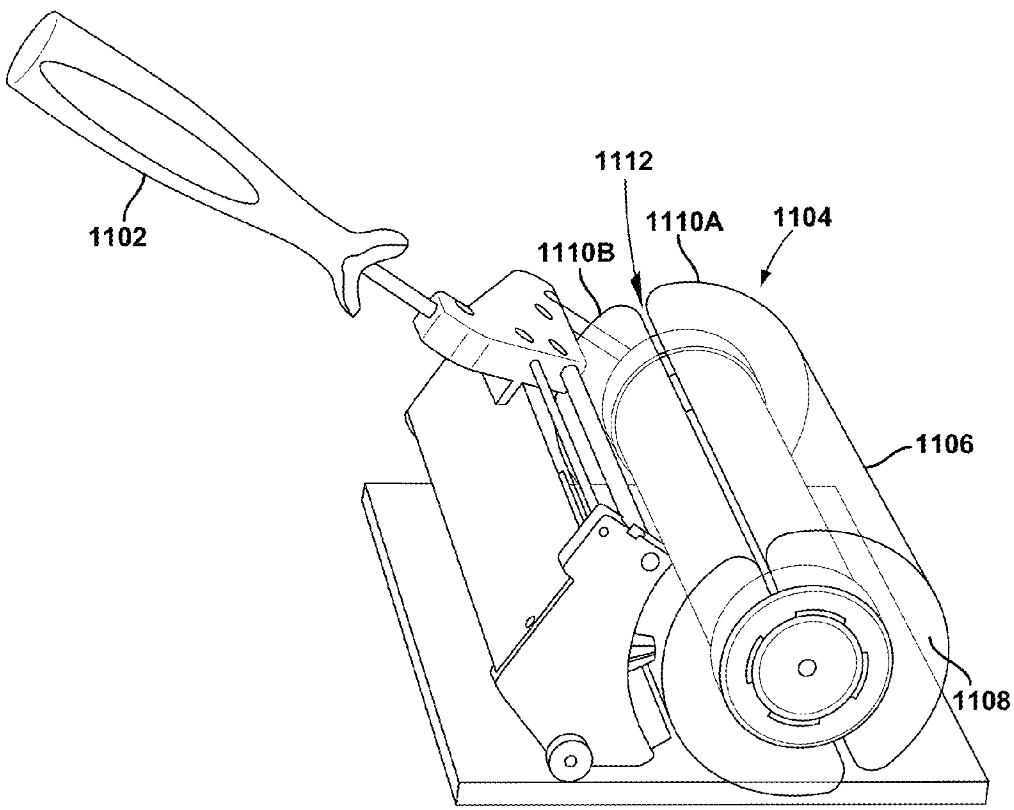

FIGURE 11A

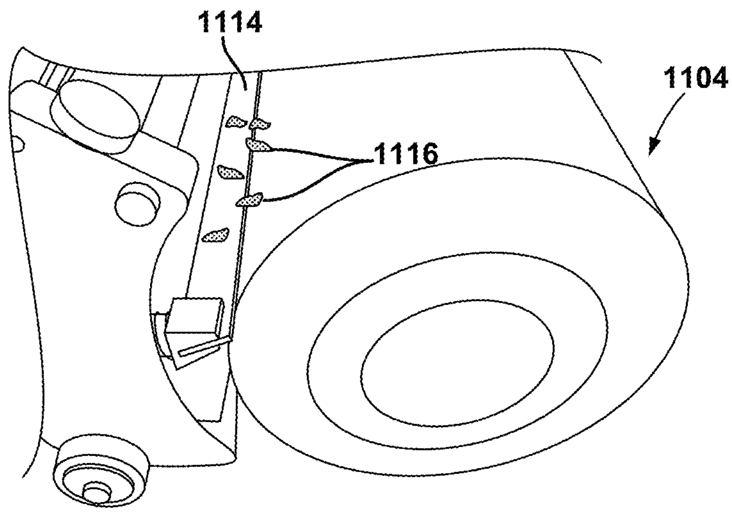

FIGURE 11B

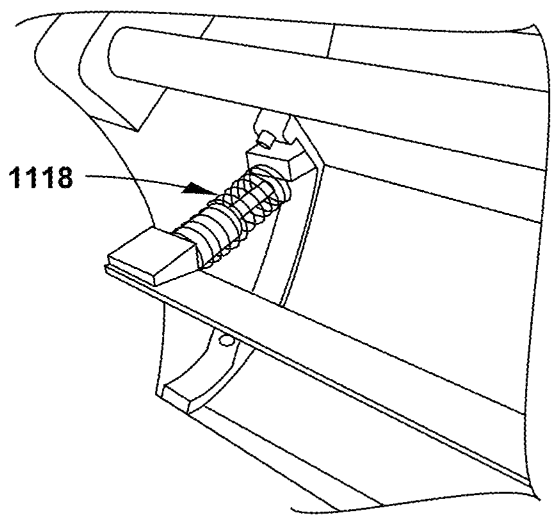

FIGURE 11C

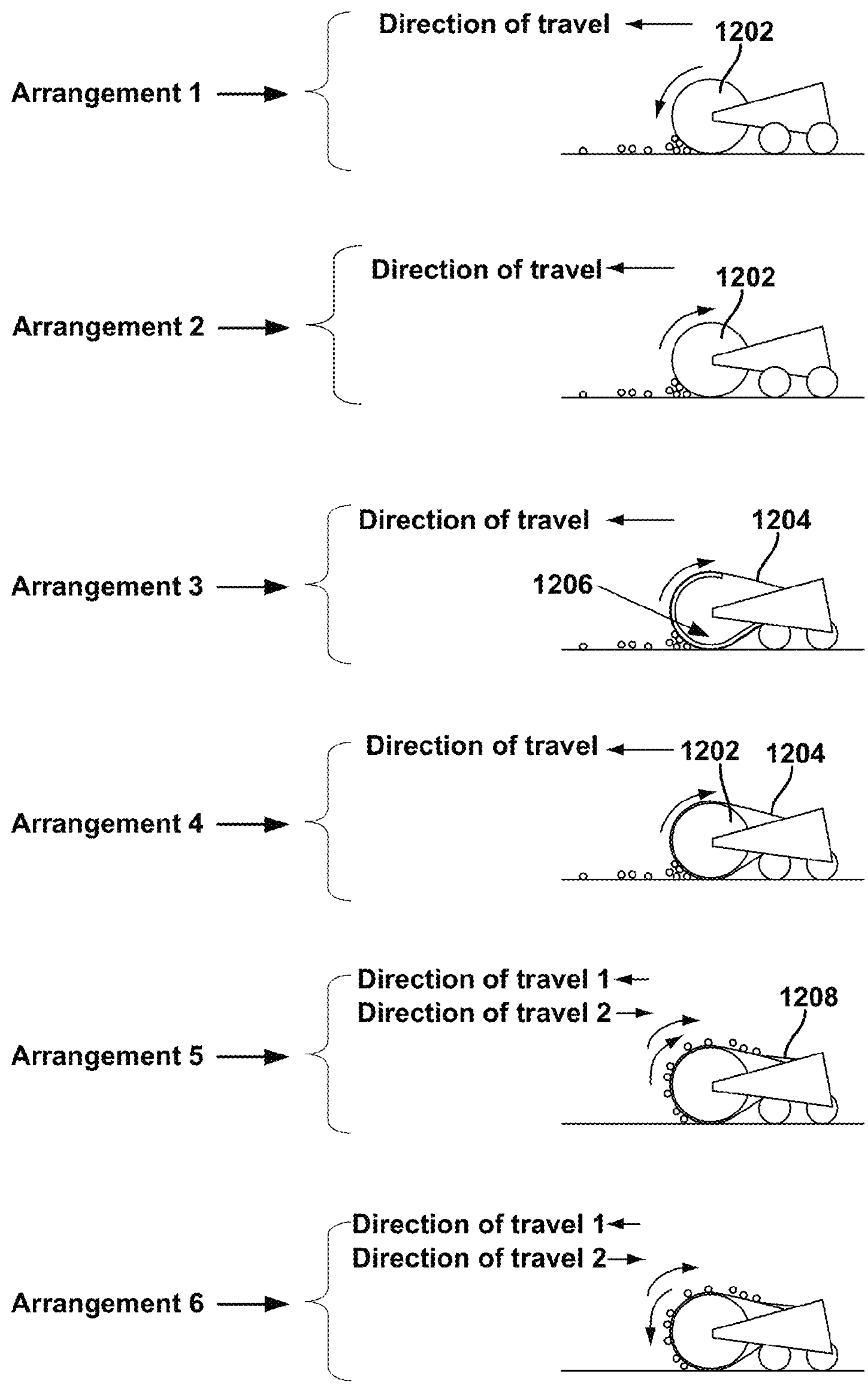
Arrangement 1
Direction of travel
1202
Arrangement 2
Direction of travel
1202
Arrangement 3
Direction of travel
1204
1206
Arrangement 4
Direction of travel
1202
1204
Arrangement 5
Direction of travel 1
Direction of travel 2
1208
Arrangement 6
Direction of travel 1
Direction of travel 2

FIGURE 12

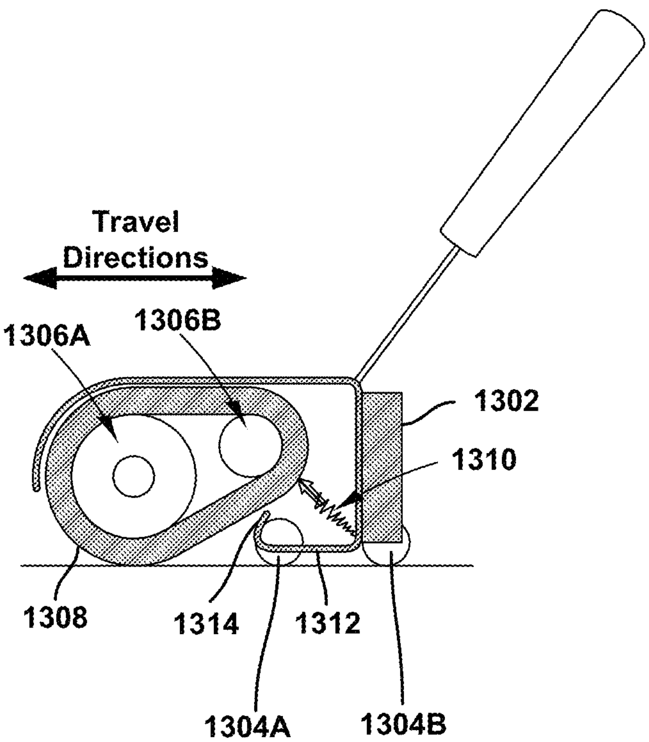
Travel
Directions
1306A
1306B
1302
1310
1308
1314
1312
1304A
1304B

FIGURE 13

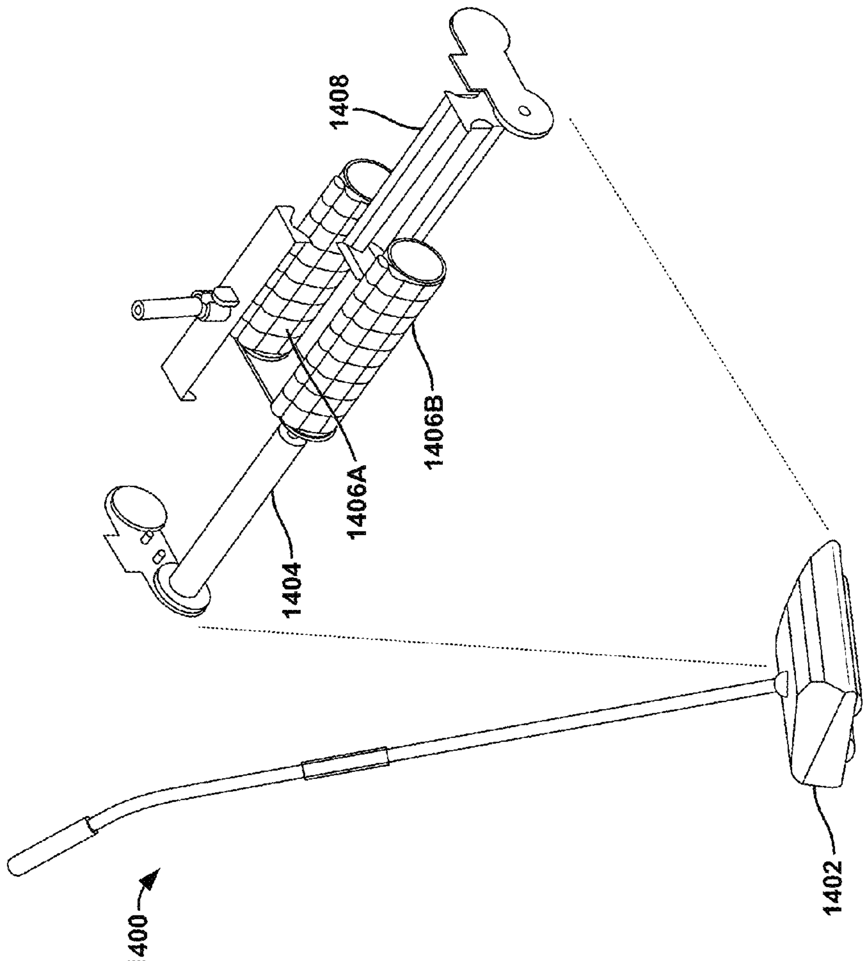

FIGURE 14A

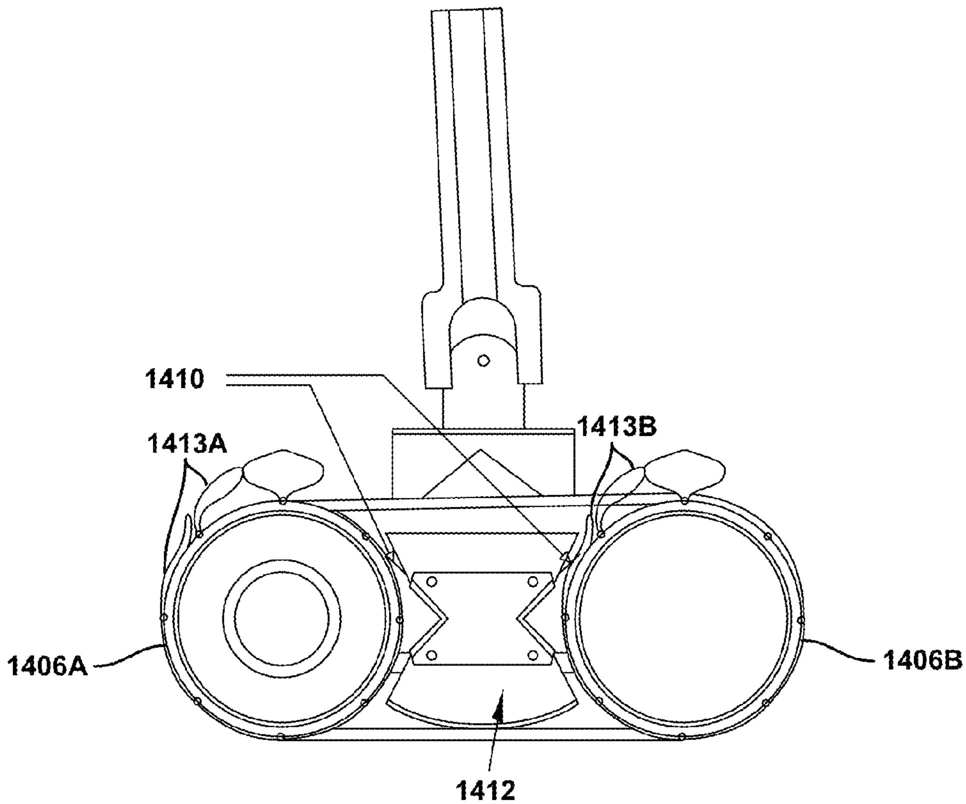

FIGURE 14B

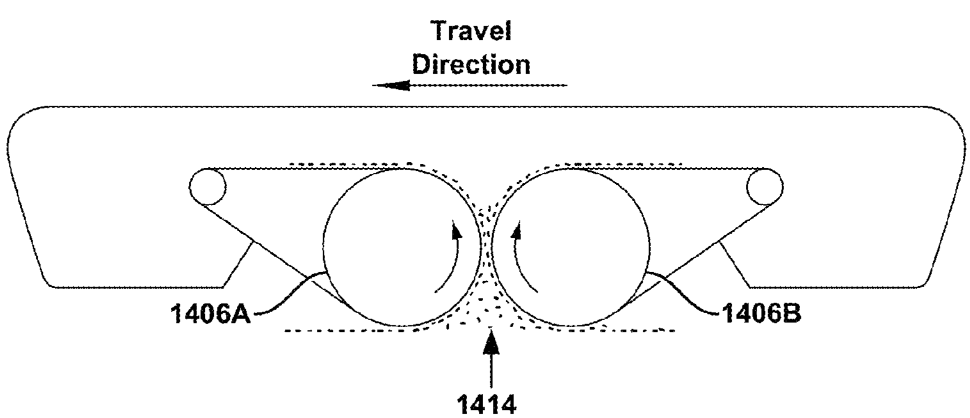

FIGURE 14C

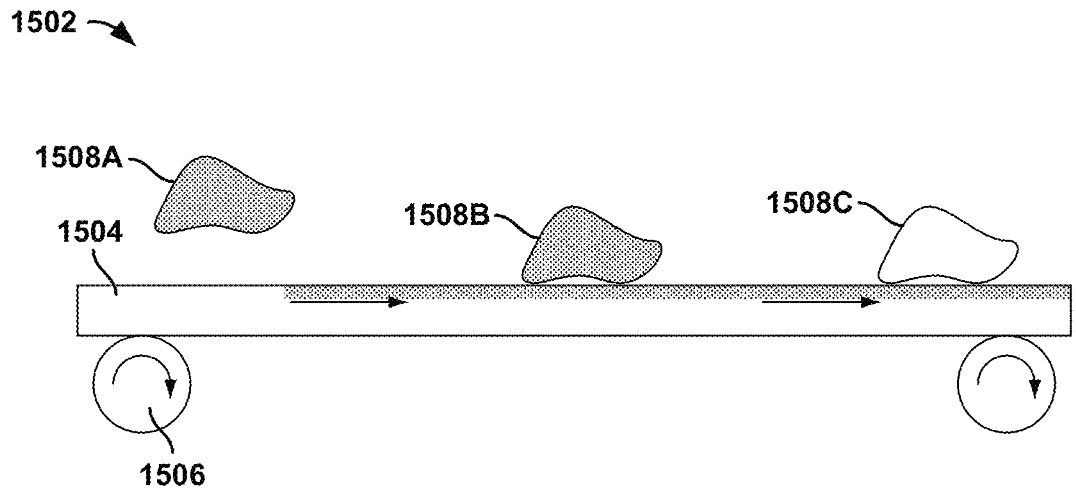

FIGURE 15

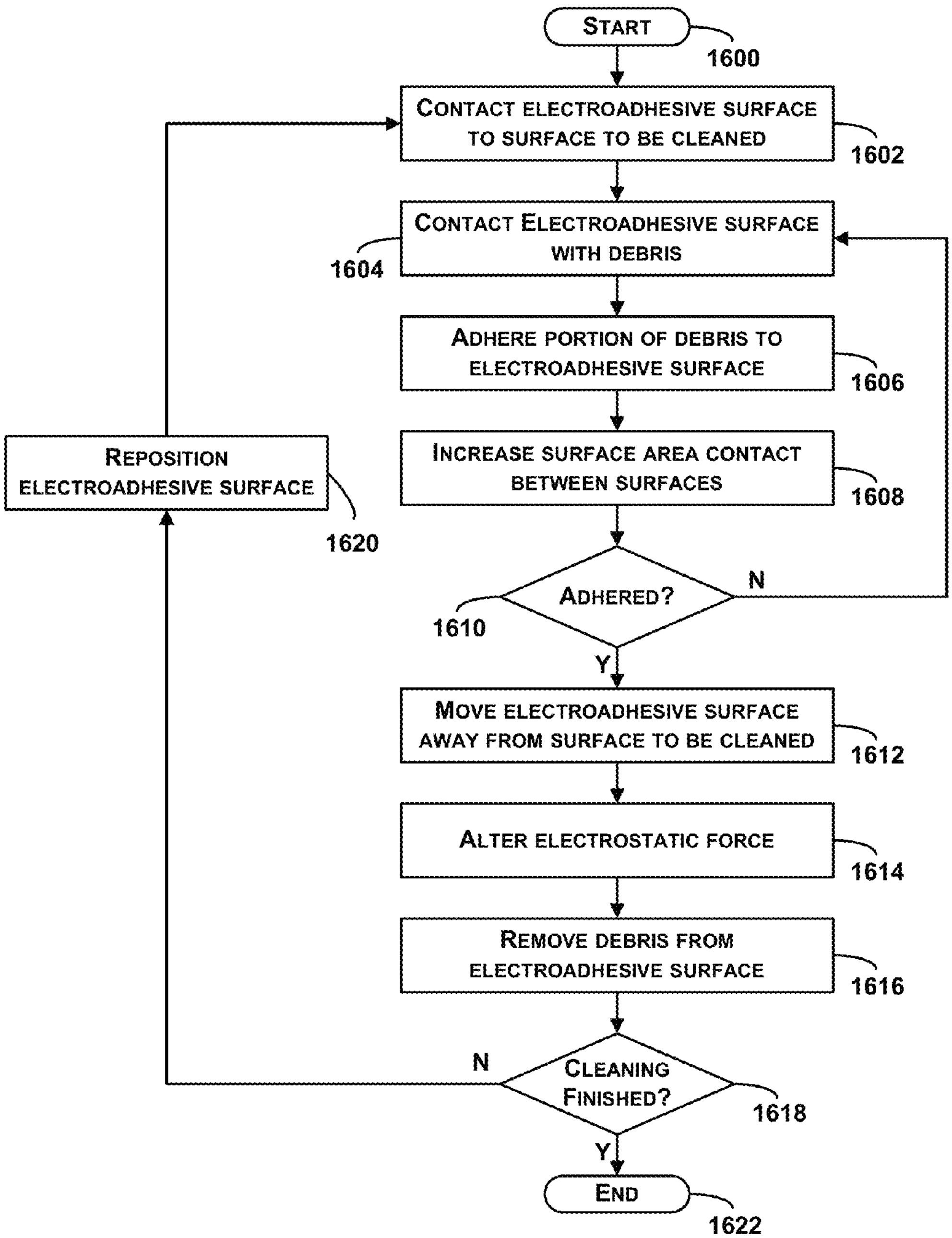
START
1600
CONTACT ELECTROADHESIVE SURFACE TO SURFACE TO BE CLEANED
1602
CONTACT ELECTROADHESIVE SURFACE WITH DEBRIS
1604
ADHERE PORTION OF DEBRIS TO ELECTROADHESIVE SURFACE
1606
INCREASE SURFACE AREA CONTACT BETWEEN SURFACES
1608
ADHERED?
1610
N
Y
MOVE ELECTROADHESIVE SURFACE AWAY FROM SURFACE TO BE CLEANED
1612
ALTER ELECTROSTATIC FORCE
1614
REMOVE DEBRIS FROM ELECTROADHESIVE SURFACE
1616
CLEANING FINISHED?
1618
N
Y
END
1622
REPOSITION ELECTROADHESIVE SURFACE
1620

FIGURE 16

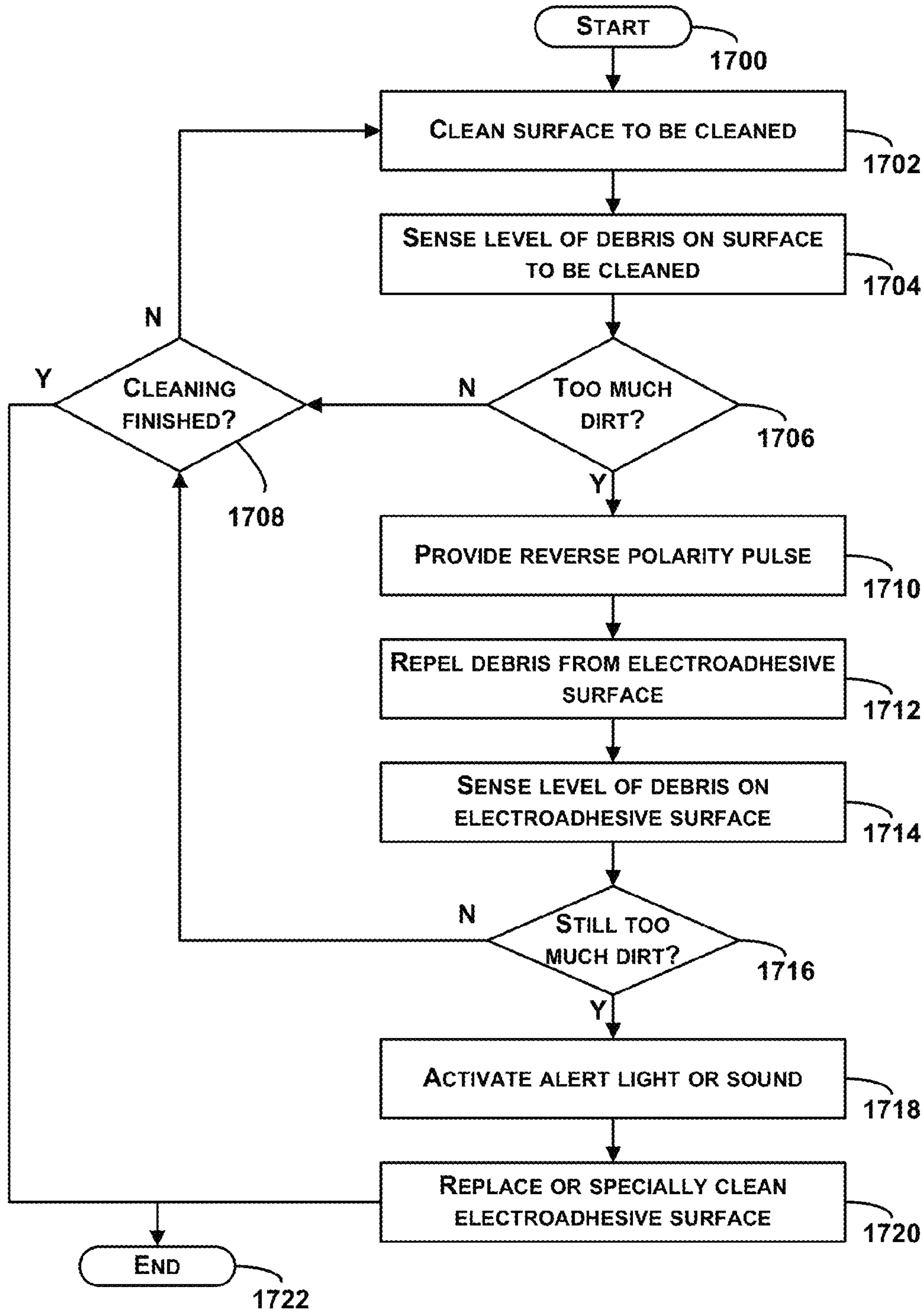
START
1700
CLEAN SURFACE TO BE CLEANED
1702
SENSE LEVEL OF DEBRIS ON SURFACE TO BE CLEANED
1704
N
Y
CLEANING FINISHED?
1708
N
TOO MUCH DIRT?
1706
Y
PROVIDE REVERSE POLARITY PULSE
1710
REPEL DEBRIS FROM ELECTROADHESIVE SURFACE
1712
SENSE LEVEL OF DEBRIS ON ELECTROADHESIVE SURFACE
1714
N
STILL TOO MUCH DIRT?
1716
Y
ACTIVATE ALERT LIGHT OR SOUND
1718
REPLACE OR SPECIALLY CLEAN ELECTROADHESIVE SURFACE
1720
END
1722

FIGURE 17

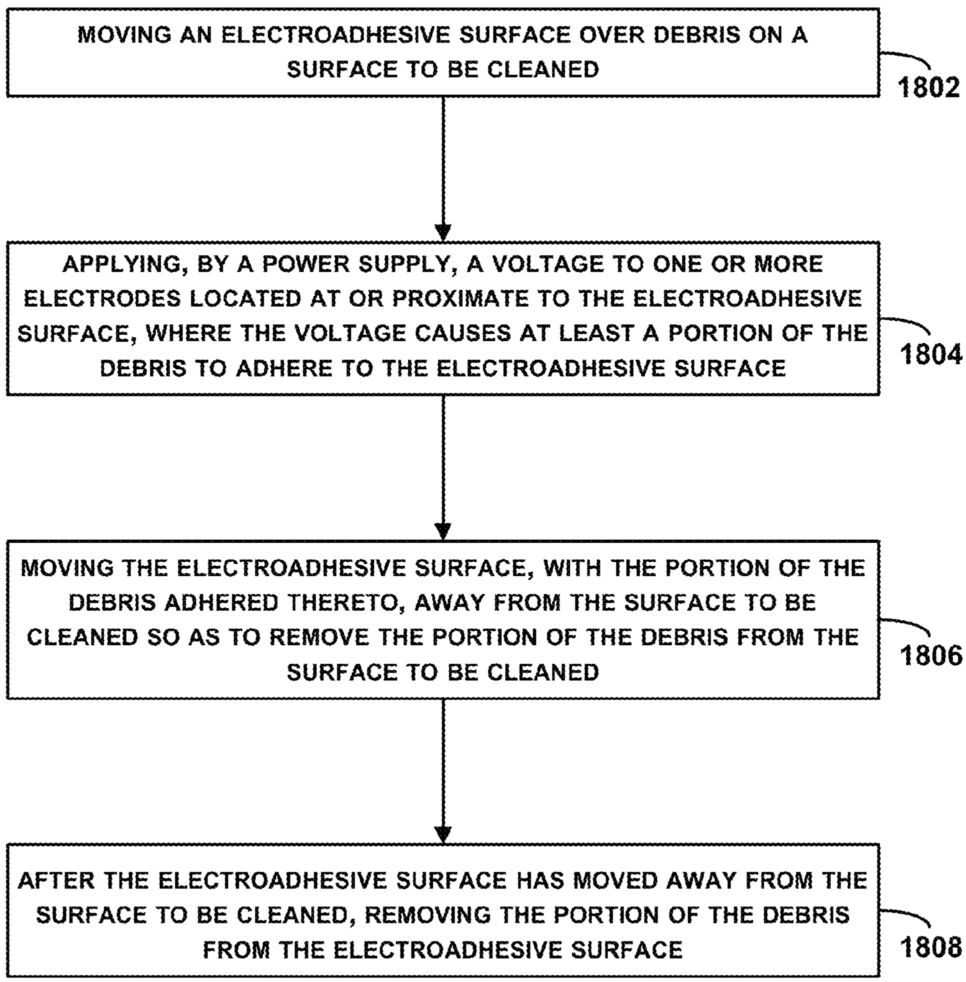
MOVING AN ELECTROADHESIVE SURFACE OVER DEBRIS ON A SURFACE TO BE CLEANED
1802
APPLYING, BY A POWER SUPPLY, A VOLTAGE TO ONE OR MORE ELECTRODES LOCATED AT OR PROXIMATE TO THE ELECTROADHESIVE SURFACE, WHERE THE VOLTAGE CAUSES AT LEAST A PORTION OF THE DEBRIS TO ADHERE TO THE ELECTROADHESIVE SURFACE
1804
MOVING THE ELECTROADHESIVE SURFACE, WITH THE PORTION OF THE DEBRIS ADHERED THERETO, AWAY FROM THE SURFACE TO BE CLEANED SO AS TO REMOVE THE PORTION OF THE DEBRIS FROM THE SURFACE TO BE CLEANED
1806
AFTER THE ELECTROADHESIVE SURFACE HAS MOVED AWAY FROM THE SURFACE TO BE CLEANED, REMOVING THE PORTION OF THE DEBRIS FROM THE ELECTROADHESIVE SURFACE
1808

FIGURE 18

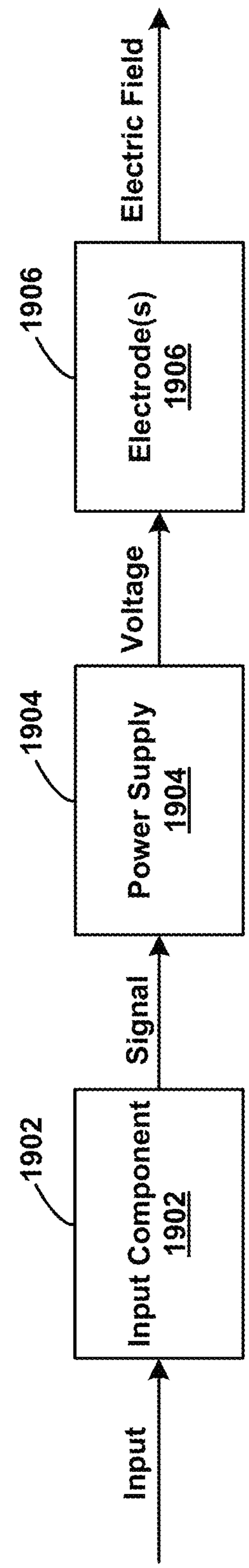
Input
Input Component
1902
1902
Signal
Power Supply
1904
1904
Voltage
Electrode(s)
1906
1906
Electric Field

FIGURE 19

ELECTROADHESIVE SURFACE CLEANER

CROSS REFERENCE TO RELATED APPLICATION

The present application is a continuation-in-part of Patent Cooperation Treaty application PCT/US12/30454, filed Mar. 23, 2012, which claims priority to U.S. provisional application Ser. No. 61/466,907, filed Mar. 23, 2011. The present application also claims priority to U.S. provisional application Ser. No. 61/731,185, filed Nov. 29, 2012, and U.S. provisional application Ser. No. 61/658,335, filed on Jun. 11, 2012. All priority applications are herein incorporated by reference as if fully set forth in this description.

BACKGROUND

Cleaning devices such as wipes, sponges, brushes, brooms, mops, dusters, vacuum cleaners and the like are generally well known and widely used to clean floors and surfaces in all sorts of home, commercial and industrial environments. Such devices can be used to clean in both indoor and outdoor settings, with further traditionally outdoor devices such as rakes, mowers, blowers and the like having various applications across numerous other settings as well. Many of these devices and tools require a significant amount of manual labor to be useful, such that a wide variety powered implementations, features and other improvements have been provided for many such cleaning devices over the years to help users in this regard.

SUMMARY

The present disclosure describes embodiments that relate to an electroadhesive surface cleaner. In one aspect, a device is described. The device comprises at least one electroadhesive surface positioned at or proximate to one or more electrodes and configured to interact with debris on a surface to be cleaned. The device also comprises a power supply configured to apply an input voltage to the one or more electrodes to thereby cause at least a portion of the debris to adhere to the electroadhesive surface. The at least one electroadhesive surface is configured to move, with the portion of the debris adhered thereto, away from the surface to be cleaned so as to remove the portion of the debris from the surface to be cleaned.

In another aspect, a system is described. The system comprises at least one electroadhesive surface positioned at or proximate to one or more electrodes and configured to interact with debris on a surface to be cleaned. The system also comprises a power supply configured to apply an input voltage to the one or more electrodes to thereby cause at least a portion of the debris to adhere to the electroadhesive surface. The at least one electroadhesive surface is configured to move, with the portion of the debris adhered thereto, away from the surface to be cleaned so as to remove the portion of the debris from the surface to be cleaned. The system further comprises a removal component configured to facilitate removal of the portion of the debris adhered to the electroadhesive surface after the portion has been removed from the surface to be cleaned.

In still another aspect, a method is described. The method comprises moving an electroadhesive surface over debris on a surface to be cleaned. The method also comprises applying, by a power supply, a voltage to one or more electrodes located at or proximate to the electroadhesive surface. The voltage causes at least a portion of the debris to adhere to the electroadhesive surface. The method further comprises moving the electroadhesive surface, with the portion of the debris adhered thereto, away from the surface to be cleaned so as to remove the portion of the debris from the surface to be cleaned. The method also comprises, after the electroadhesive surface has moved away from the surface to be cleaned, removing the portion of the debris from the electroadhesive surface.

The foregoing summary is illustrative only and is not intended to be in any way limiting. In addition to the illustrative aspects, embodiments, and features described above, further aspects, embodiments, and features will become apparent by reference to the figures and the following detailed description.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1**A illustrates an electroadhesive device in side cross-sectional view, in accordance with an example embodiment.

FIG. **1**B illustrates the electroadhesive device of FIG. **1**A adhered to a foreign object in side cross-sectional view, in accordance with an example embodiment.

FIG. **1**C illustrates close-up side cross-sectional view an electric field formed in the foreign object of FIG. **1**B as result of the voltage difference between electrodes in the adhered electroadhesive device, in accordance with an example embodiment.

FIG. **1**D illustrates design parameters of an electroadhesive device, in accordance with an example embodiment.

FIG. **2**A illustrates in side cross-sectional view a pair of electroadhesive surfaces or devices having single electrodes thereon, in accordance with example embodiments.

FIG. **2**B illustrates in side cross-sectional view the pair of electroadhesive surfaces or devices of FIG. **2**A with voltage applied thereto, in accordance with example embodiments.

FIG. **3**A illustrates in top perspective view an electroadhesive surface in the form of a sheet with electrodes patterned on top and bottom surfaces thereof, in accordance with an example embodiment.

FIG. **3**B illustrates in top perspective view an alternative electroadhesive surface in the form of a sheet with electrodes patterned on a single surface thereof, in accordance with an example embodiment.

FIG. **4**A illustrates in side cross-sectional regular and close-up views a deformable electroadhesive device conforming to the shape of a rough surface on a foreign object, in accordance with an example embodiment.

FIG. **4**B illustrates in partial side cross-sectional view a surface of a deformable electroadhesive device initially when the device is brought into contact with a surface of a structure or foreign object, in accordance with an example embodiment.

FIG. **4**C illustrates in partial side cross-sectional view the surface shape of electroadhesive device of FIG. **4**B and foreign object surface after some deformation in the electroadhesive device due to the initial force of electrostatic attraction and compliance, in accordance with an example embodiment.

FIG. **5** illustrates in side cross-sectional view an electroadhesive device having a plurality of smaller foreign objects adhered thereto, in accordance with an example embodiment.

FIG. **6**A illustrates in front perspective view an electroadhesive cleaning pad with its power supply turned off, in accordance with an example embodiment.

FIGS. **6**B-**6**E illustrate in front perspective view the electroadhesive cleaning pad of FIG. **6**A with its power supply turned on and various types of particulate matter being adhered thereto, in accordance with an example embodiment.

FIG. **7**A illustrates in side elevation view an active electroadhesive cleaning device having hair or fibers along its electroadhesive surface, in accordance with an example embodiment.

FIG. **7**B in side elevation view an active electroadhesive cleaning device having a plurality of extendable flaps along its electroadhesive surface, in accordance with an example embodiment.

FIG. **8**A illustrates in top plan view a checkerboard type electrode pattern for use with respect to a suitable electroadhesive surface, in accordance with an example embodiment.

FIG. **8**B illustrates in top plan view the checkerboard type electrode pattern of FIG. **8**A having an alternatively charged configuration, in accordance with an example embodiment.

FIG. **9**A illustrates in top plan view an interdigitated electrode pattern of straight stripes for use with respect to a suitable electroadhesive surface, in accordance with an example embodiment.

FIG. **9**B illustrates in top plan view an interdigitated electrode pattern of diagonal stripes for use with respect to a suitable electroadhesive surface, in accordance with an example embodiment.

FIG. **9**C illustrates in top plan view an interdigitated electrode pattern incorporating multiple repetitions of the pattern in FIG. **9**A, in accordance with an example embodiment.

FIG. **9**D illustrates in top plan view an electroadhesive surface of an electroadhesive cleaning device having an extended electrode pattern incorporating multiple repetitions of the pattern in FIG. **9**C, in accordance with an example embodiment.

FIG. **10**A illustrates a track-based electroadhesive cleaning device, in accordance with an example embodiment.

FIG. **10**B illustrates a zoomed-in view of the track configuration for the electroadhesive cleaning device in FIG. **10**A, in accordance with an example embodiment.

FIG. **10**C illustrates portion of an alternative track-based electroadhesive cleaning device, in accordance with an example embodiment.

FIG. **10**D illustrates the track-based electroadhesive cleaning device cleaning a surface, in accordance with an example embodiment.

FIG. **10**E illustrates in side perspective view an alternative track-based electroadhesive cleaning device having ion charge sprayers, in accordance with an example embodiment.

FIG. **10**F illustrates a cleaning arrangement for a track-based electroadhesive cleaning device, in accordance with an example embodiment.

FIG. **10**G illustrates the electroadhesive cleaning device having a tray to collect debris, in accordance with an example embodiment.

FIG. **10**H illustrates a back view of a track-based electroadhesive cleaning device, in accordance with an example embodiment.

FIG. **10**I illustrates a modular track-based electroadhesive cleaning device with the tray to collect debris and replaceable belt or replaceable roller, in accordance with an example embodiment.

FIG. **11**A illustrates an alternative arrangement for an electroadhesive cleaning device, in accordance with an example embodiment.

FIG. **11**B illustrates a scraper in contact with the roller to remove debris removed during rotation of the roller, in accordance with an example embodiment.

FIG. **11**C illustrates a back view of the electroadhesive cleaning device showing a spring-loaded scraper, in accordance with an example embodiment.

FIG. **12** illustrates various arrangements depicting respective rotational configurations for roller-based and track-based electroadhesive cleaning devices, in accordance with example embodiments.

FIG. **13** illustrates an arrangement depicting a battery powering an electroadhesive cleaning device, in accordance with an example embodiment.

FIG. **14**A illustrates an electroadhesive cleaning device **1400** having two rollers, in accordance with an example embodiment.

FIG. **14**B illustrates another view of the rollers illustrated in FIG. **14**A, in accordance with an example embodiment.

FIG. **14**C illustrates an electroadhesive cleaning device having two rollers rotating in opposite directions, in accordance with an example embodiment.

FIG. **15** illustrates in side elevation view a conveyor belt based electroadhesive cleaning system, in accordance with an example embodiment.

FIG. **16** is a flowchart of a method of cleaning debris from a surface, in accordance with an example embodiment.

FIG. **17** is a flowchart of a method of electroadhesive cleaning involving reusing an electroadhesive surface, in accordance with an example embodiment.

FIG. **18** is a flowchart of a method of electroadhesive cleaning of a surface having debris thereon, in accordance with an example embodiment.

FIG. **19** is a block diagram illustrating providing a voltage by a power supply to electrodes based on a user-input, in accordance with an example embodiment.

DETAILED DESCRIPTION

The following detailed description describes various features and functions of the disclosed systems and methods with reference to the accompanying figures. In the figures, similar symbols identify similar components, unless context dictates otherwise. The illustrative system and method embodiments described herein are not meant to be limiting. It may be readily understood that certain aspects of the disclosed systems and methods can be arranged and combined in a wide variety of different configurations, all of which are contemplated herein.

The present disclosure describes various embodiments to devices, systems and methods involving active electrostatic cleaning applications. In various examples, the subject cleaning devices, systems or methods can utilize an active electroadhesion component that includes a power source and one or more electrodes that are arranged to generate specific and controllable electroadhesive forces with respect to one or more particles, debris, or other foreign objects to be cleaned. The term "active" generally refers to a controlled, power source based, and/or more powerful/higher charge application of electroadhesion and electrostatic principles, in contrast with the generally uncontrolled and typically low charge nature of electrostatic cling that is inherently generated by and featured in traditional electrostatic dusters and other similar items.

While the various examples disclosed herein focus on particular aspects of specific electroadhesive applications, it will be understood that the various principles and examples disclosed herein can be applied to other electrostatic applications and arrangements as well. For example, an electrolaminate application involving one or more electrostatically charged sheets can utilize the same types of electrodes and general electrostatic principles for cleaning and otherwise controlling particles, debris, and other foreign objects. Furthermore, while the particular applications described herein are made with respect to cleaning or handling particles and other items by way of electroadhesive forces, the various electrodes and materials therefore provided herein can be used in a variety of other applications that are not restricted to such environments.

As the term is used herein, “electroadhesion” refers to the mechanical coupling of two objects using electrostatic forces. Electroadhesion as described herein uses electrical control of these electrostatic forces to permit temporary and detachable attachment between two objects. This electrostatic adhesion holds two surfaces of these objects together or increases the traction or friction between two surfaces due to electrostatic forces created by an applied electrical field. Although electrostatic clamping has traditionally been limited to holding two flat, smooth and generally conductive surfaces separated by a highly insulating material together, the various examples provided herein can involve electroadhesion devices and techniques that do not limit the material properties, curvatures, size or surface roughness of the objects subject to electroadhesive forces and handling. Furthermore, while the various examples and discussions provided herein typically involve electrostatically adhering a particle, debris, or other foreign item to a cleaning device, it will also be understood that many other types of electrostatic applications may also generally be implicated for use with the disclosed examples. For example, two components of the same device may be electrostatically adhered to each other, such as in an electrolaminate or other type of arrangement.

I. Overview

Controlled use of active electroadhesion can facilitate improved cleaning for such devices and methods. An electroadhesive cleaning device or system can be adapted to clean debris, or move one or more foreign objects, away from a surface to be cleaned. The device or system can include one or more electrodes adapted to produce one or more electroadhesive forces from an input voltage, one or more input components configured to accept and facilitate user input to control the input voltage, and at least one interactive electroadhesive surface positioned proximate and/or distal to the electrode(s) and configured to interact with one or more foreign objects to be cleaned.

A separate respective electroadhesive force can be generated for each foreign object to be cleaned, and each such electroadhesive force can suitably adhere its respective foreign object to the electroadhesive surface or elsewhere on the cleaning device. The electroadhesive surface or surfaces can be arranged to permit the passage of the electroadhesive force(s) therethrough, such that the foreign object(s) are adhered thereagainst. In addition, the electroadhesive surface(s) can be further configured to facilitate the ready removal of the foreign object(s) therefrom, such as when the electroadhesive force(s) are controllably altered. Such altering can be a reduction, removal or reversal of the electroadhesive force(s). The foreign object(s) can also be physically removed without necessarily altering the electroadhesive force(s), such as by using mechanical forces such as those provided by a dust brush in contact with the electroadhesive surface(s), a non-contact electrostatic plate that attracts dust away from the electroadhesive surface onto itself, a fluid jet that washes or blows away items, or a localized vacuum that pulls dust away from the electroadhesive surface, for example.

In examples, the foreign object(s) can include debris such as dust, dirt, pebbles, crumbs, hair, garbage and/or other particulate matter to be cleaned. In some examples, the electroadhesive surface can include a plurality of cilia, a plurality of flaps, one or more light adhesives, and/or any of a variety of materials, such as soft, tacky, fabric, fiber, cloth, plastic and/or other suitable materials. In some examples, at least a portion of the electroadhesive surface can comprise a deformable (or compliant) surface, such that a respective portion of the deformable surface moves closer to (i.e., comply with a shape of) at least one of the foreign objects when the electroadhesive force is applied.

In examples, the electroadhesive cleaning device or system can include an active power source coupled to one or more input components and one or more electrodes, where the active power source is configured to facilitate providing the input voltage to the one or more electrodes. In addition, in some examples, the device may include one or more rollers coupled to the electroadhesive surface and configured to rotate the electroadhesive surface with respect to a foreign surface such that a new, clean portion of the electroadhesive surface is controllably presented to the remaining foreign objects or debris regardless of motion of the electroadhesive cleaning device as a whole. In such arrangements, the electroadhesive surface(s) can be configured as a continuous track that moves with respect to a rotational motion of the one or more rollers.

In some examples, a removal component or components can be configured to facilitate the removal of the one or more foreign objects from the electroadhesive surface after the one or more foreign objects have been displaced from the surface to be cleaned. For such a removal component, for example, the electrode(s) can be further adapted to produce collectively one or more reverse polarity pulses, such that one or more repellant forces suitably repel one or more foreign objects or debris away from the active electroadhesive cleaning device when the charges are controllable reversed.

In examples, the electrodes can include a plurality of oppositely chargeable electrodes arranged into a pattern. Such a pattern can involve an interdigitated pattern or portion having a plurality of differing pitches. Such differing pitches can be configured to clean foreign objects or debris of correspondingly different sizes, and the interdigitated electrode pattern may be configured to actuate the plurality of differing pitches selectively. In this manner, the size of the foreign objects to be cleaned can be designated, such as by a user input. In some examples, one or more sensors can be coupled to the electroadhesive surface and configured to detect the amount of foreign objects or debris adhered thereto. Such sensors can be used to aid in the removal of particular matter from the electroadhesive surface in some cases. Alternatively, or in addition, such sensors can indicate to the user that it is time for thorough cleaning or replacement of the electroadhesive surface(s).

In still further examples, the device or system can include an ion charge sprayer positioned proximate the electroadhesive surface and adapted to spray a plurality of ionic charges onto the foreign object(s), such that at least a portion of the respective electroadhesive force(s) result from the presence of the ionic charges on the foreign object(s). In such examples, exactly one electrode can be used, with that exactly one electrode being adapted to carry a charge of the opposite polarity from the plurality of ionic charges.

In other examples, various methods of physically cleaning the debris or the one or more foreign objects are provided. Such methods can involve cleaning a plurality of foreign objects or debris away from a surface to be cleaned, for example. Process steps can include contacting an electroadhesive surface to each of a plurality of foreign objects situated about the surface to be cleaned, applying an electrostatic adhesion voltage in a controlled manner across one or more electrodes located proximate the electroadhesive surface, adhering each of the plurality of foreign objects to the electroadhesive surface via respective electrostatic attraction forces, moving the electroadhesive surface away from the surface to be cleaned while the plurality of foreign objects remain adhered thereto, altering the electrostatic adhesion voltage in a controlled manner, and removing the plurality of foreign objects from the electroadhesive surface after the electrostatic adhesion voltage has been altered. Similar to the foregoing, the electrostatic adhesion voltage can be sufficient to generate a separate respective electrostatic attraction force through at least a portion of the electroadhesive surface with respect to each of the plurality of foreign objects situated about the surface to be cleaned. In some examples, the surface to be cleaned can be the ground, floor, a vertical surface such as a wall or another other relevant surface to be cleaned. In some examples, the step of altering the electrostatic adhesion voltage can include reversing the polarity of the voltage. Such a feature can result in repelling the foreign object(s) away from the electroadhesive surface in a controlled manner at a desired time. In examples, in addition or alternative to modifying the voltage, electrostatic adhesion can be altered by mechanically moving a portion of the electroadhesive surface away from or off of the electrodes in order to remove the foreign objects from the electroadhesive surface.

Other apparatuses, methods, features and advantages of the invention will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features and advantages be included within this description, be within the scope of the invention, and be protected by the accompanying claims.

Referring now to the Figures, FIG. **1**A illustrates an electroadhesive device in elevated cross-sectional view, in accordance with an example embodiment. Electroadhesive device **100** includes one or more electrodes **102** located at or near an electroadhesive gripping surface **104** thereof, as well as an insulating material **106** between electrodes **102** and a backing **108** or other supporting structural component. For purposes of illustration, electroadhesive device **100** is shown as having six electrodes in three pairs; however, more or fewer electrodes can be used in a given electroadhesive device. Where a single electrode is used in a given electroadhesive device, a complimentary electroadhesive device having at least one electrode of the opposite polarity can be used therewith. With respect to size, electroadhesive device **100** is substantially scale invariant. That is, electroadhesive device sizes may range from less than 1 square centimeter to greater than several meters in surface area, for example. Larger and smaller surface areas also possible, and may be sized based on a given application.

Although electroadhesive device **100** having electroadhesive gripping surface **104** of FIG. **1**A is shown as having six electrodes **102**, it will be understood that a given electroadhesive device or gripping surface can have a single electrode. Furthermore, a given electroadhesive device can have a plurality of different electroadhesive gripping surfaces, with each separate electroadhesive gripping surface having at least one electrode and being configured to be placed against or in close proximity to the foreign object to be gripped. Although the terms electroadhesive device, electroadhesive gripping unit and electroadhesive gripping surface are all used herein to designate electroadhesive components of interest, these various terms can be used interchangeably in various contexts. In particular, while a given electroadhesive device might comprise numerous distinct "gripping surfaces," these different gripping surfaces might themselves also be considered separate "devices" or alternatively "end effectors."

FIG. **1**B depicts in elevated cross-sectional view the electroadhesive device **100** of FIG. **1**A adhered to a foreign object **110**, in accordance with an example embodiment. Foreign object **110** includes surface **112** and inner material **114**. Electroadhesive gripping surface **104** of electroadhesive device **100** is placed against or nearby surface **112** of foreign object **110**. An electrostatic adhesion voltage is then applied via electrodes **102** using external control electronics (not shown) in electrical communication with the electrodes **102**. As shown in FIG. **1**B, the electrostatic adhesion voltage may comprise alternating positive and negative charges on neighboring electrodes **102**. As result of the voltage difference between electrodes **102**, one or more electroadhesive forces are generated, which electroadhesive forces act to hold the electroadhesive device **100** and foreign object **110** to each other. Due to the nature of the forces being applied, electroadhesive device **100** may be adhered to foreign object **110** without actual contact. For example, a piece of paper, thin film, or other material or substrate may be placed between electroadhesive device **100** and foreign object **110**. Furthermore, although the term "contact" is used herein to denote the interaction between an electroadhesive device and a foreign object, direct surface to surface contact is not always required, such that one or more thin objects such as an insulator, can be disposed between an electroadhesive gripping surface and the foreign object. In some examples such an insulator between the gripping surface and foreign object can be a part of the device, while in others it can be a separate item or device.

FIG. **1**C illustrates in elevated cross-sectional close-up view an electric field formed in the foreign object **110** of FIG. **1**B as a result of the voltage difference between electrodes in the adhered electroadhesive device **100**, in accordance with an example embodiment. While the electroadhesive device **100** is placed against foreign object **110** and an electrostatic adhesion voltage is applied, an electric field **116** forms in the inner material **114** of the foreign object **110**. The electric field **116** locally polarizes inner material **114** or induces direct charges on material locally opposite to the charge on the electrodes **102** of the device, and thus causes electrostatic adhesion between the electrodes **102** (and overall device **100**) and the induced charges on the foreign object **110**. The induced charges may be the result of a dielectric polarization or from weakly conductive materials and electrostatic induction of charge. In the event that the inner material **114** is a strong conductor, such as copper for example, the induced charges may completely cancel the electric field **116**. In this case the internal electric field **116** may be zero, but the induced charges nonetheless still form and provide electrostatic force to the device **100**. An insulator may also be provided between the device **100** and foreign object **110** in instances where material **114** is copper or another strong conductor.

Thus, the electrostatic adhesion voltage provides an overall electrostatic force, between the electroadhesive device **100** and inner material **114** beneath surface **112** of foreign object **110**, which electrostatic force maintains the current position of the electroadhesive device **100** relative to the surface of the foreign object **110**. The overall electrostatic force may be sufficient to overcome the gravitational pull on the foreign object **110**, such that the electroadhesive device **100** may be used to hold the foreign object **110** aloft. In examples, a plurality of electroadhesive devices may be placed against foreign object **110**, such that additional electrostatic forces against the object can be provided. Furthermore, the foreign object **110** may not be larger than the electroadhesive device **100** in all or any dimension, and it is contemplated that the foreign object **110** can be significantly smaller than the electroadhesive device in some examples. The combination of electrostatic forces may be sufficient to lift, move, pick and place, or otherwise handle the foreign object **110**. Electroadhesive device **100** may also be attached to other structures and hold these additional structures aloft, or it may be used on sloped or slippery surfaces to increase normal friction forces.

Removal of the electrostatic adhesion voltages from electrodes **102** ceases the electrostatic adhesion force between electroadhesive device **100** and the surface **112** of foreign object **110**. Thus, when there is no electrostatic adhesion voltage between electrodes **102**, electroadhesive device **100** can move more readily relative to surface **112**. This condition allows the electroadhesive device **100** to move before and after an electrostatic adhesion voltage is applied. Well controlled electrical activation and de-activation enables fast adhesion and detachment, such as response times less than about 50 milliseconds, for example, while consuming relatively small amounts of power. Larger release times may also be valuable in many applications.

Electroadhesive device **100** includes electrodes **102** on an outside surface **104** of an insulating material **106**. This example may be well suited for controlled attachment to insulating and weakly conductive inner materials **114** of various foreign objects **110**. Other electroadhesive device **100** relationships between electrodes **102** and insulating materials **106** are also contemplated and suitable for use with a broader range of materials, including conductive materials. For example, a thin electrically insulating material (not shown) can be located on the surfaces of the electrodes where surface **112** is on a metallic object. A shorter distance between surfaces **104** and **112** results in a stronger electroadhesive force between the objects. Accordingly, a deformable surface **104** configured to at least partially conform to the surface **112** of the foreign object **110** can be used.

As the term is used herein, an electrostatic adhesion voltage refers to a voltage that produces a suitable electrostatic force to couple electroadhesive device **100** to a foreign object **110**. The minimum voltage needed for electroadhesive device **100** will vary with a number of factors, such as: the size of electroadhesive device **100**, the material conductivity and spacing of electrodes **102**, the insulating material **106**, the size of the foreign object **110**, the foreign object material **114**, the presence of any disturbances to electroadhesion such as dust, other particulates or moisture, the weight of any objects being supported by the electroadhesive force, compliance of the electroadhesive device, the dielectric and resistivity properties of the foreign object, and the relevant gaps between electrodes and foreign object surface. In one example, the electrostatic adhesion voltage includes a differential voltage between the electrodes **102** that is between about 500 volts and about 15 kilovolts. Even lower voltages may be used in micro applications. In another example, the differential voltage is between about 2 kilovolts and about 5 kilovolts. Voltage for one electrode can be zero. Alternating positive and negative charges may also be applied to adjacent electrodes **102**. The voltage on a single electrode may be varied in time, and in particular may be alternated between positive and negative charge so as to not develop substantial long-term charging of the foreign object. The resultant forces will vary with the specifics of a particular electroadhesive device **100**, the material it adheres to, any particulate disturbances, surface roughness, and so forth. In general, electroadhesion as described herein provides a wide range of clamping pressures, generally defined as the attractive force applied by the electroadhesive device divided by the area thereof in contact with the foreign object.

FIG. **1**D illustrates design parameters of an electroadhesive device, in accordance with an example embodiment. The electroadhesive device in FIG. **1**D includes foreign object **110** (a substrate to attach to, or dirt to pick up), insulating material **106**, electrodes **102**, backing material **108** (structure for load transfer through foam to rigid surface, for example), and a dielectric coating material **118**. Electroadhesion design parameters shown in FIG. **1**D can be modified to affect type and range of materials to be picked up or adhered to an electroadhesive surface. The parameters include properties of insulator material **106**, properties of dielectric coating material **118**, compliance and stiffness of the materials used, properties of electrode(s) **102**, thickness of the dielectric coating (t), width of electrodes (w), gap between successive electrodes (g), and the voltage applied to the electrodes including magnitude and waveform. These are example properties, and other properties can also affect performance of an electroadhesive device such as the electroadhesive device **100**.

The actual electroadhesion forces and pressure will vary with design and a number of factors. In an example, electroadhesive device **100** provides electroadhesive attraction pressures between about 0.7 kPa (about 0.1 psi) and about 70 kPa (about 10 psi); however, other amounts and ranges are also possible. The amount of force needed for a particular application may be readily achieved by varying the area of the contacting surfaces, varying the applied voltage, and/or varying the distance between the electrodes and foreign object surface, although other relevant factors may also be manipulated as desired.

In examples, having as much of the surface as possible covered with electrodes (i.e. minimize "g" and maximize "w") may improve clamping on "conductive" materials (metal, some kinds of wood, paper, etc.). Some conductive particles (rice, leaves, cereal etc.) may also fall in this category. However, non-conductive materials (such as some kinds of glass, almost all plastics, sand etc.) may respond to a different type of electrostatic charging which is maximized by increasing the number of electrode lines in a given area (i.e. minimize both "g" and "w"). Therefore, forces can be optimized through careful choice of "w" and "g." Generally, optimization of "w," "g", and "t" for a given surface may improve electroadhesion performance related to that surface.

Referring to FIGS. **2**A and **2**B, a pair of electroadhesive devices or gripping surfaces having single electrodes thereon is shown in side cross-sectional view, in accordance with an example embodiment. FIG. **2**A depicts electroadhesive gripping system **200**A having electroadhesive devices or gripping surfaces **202** and **204** that are in contact with the surface of a foreign object **110**, while FIG. **2**B depicts activated electroadhesive gripping system **200**B with the devices or gripping surfaces having voltage applied thereto. Electroadhesive gripping system **200**A includes two electroadhesive devices or gripping surfaces **202** and **204** that directly contact the foreign object **110**. Each electroadhesive device or gripping surface **202** and **204** has a single electrode **102** coupled thereto. In such cases, the electroadhesive gripping system can be designed to use the foreign object as an insulation material. When voltage is applied, an electric field **116** forms within foreign object **110**, and an electrostatic force between the electroadhesive devices or gripping surfaces **202** and **204** and the foreign object **110** is created. Other examples that include numerous of these single electrode electroadhesive devices are also possible.

In some examples, an electroadhesive gripping surface can take the form of a flat panel or sheet having a plurality of electrodes thereon. In other examples, the gripping surface can take a fixed shape that is matched to the geometry of the foreign object most commonly lifted or handled. For example, a curved geometry can be used to match the geometry of a cylindrical paint can or soda can. The electrodes may be enhanced by various means, such as by being patterned on an adhesive device surface to improve electroadhesive performance, or by making them using soft or flexible materials to increase compliance and thus conformance to irregular surfaces on foreign objects.

FIGS. **3**A and **3**B illustrate two examples of electroadhesive gripping surfaces in the form of flat panels or sheets with electrodes patterned on surfaces thereof shown in top perspective view, in accordance with example embodiments. FIG. **3**A shows electroadhesive gripping surface **300** in the form of a sheet or flat panel with electrodes **102** patterned on top and bottom surfaces thereof. Bottom and top electrodes sets **302** and **304** are interdigitated on opposite sides of an insulating layer **306**. In some examples, insulating layer **306** can be formed of a stiff or rigid material. In examples, the electrodes as well as the insulating layer **306** may be compliant and composed of a polymer, such as an acrylic elastomer, to increase compliance. As an example for illustration, the modulus of the polymer is below about 10 MPa; and in another example, the modulus is more specifically below about 1 MPa. Various types of compliant electrodes suitable for use are generally known, and examples are described in commonly owned U.S. Pat. No. 7,034,432, which is incorporated by reference herein in its entirety and for all purposes.

Electrode set **304** is disposed on a top surface **308** of insulating layer **306**, and includes an array of linear patterned electrodes **102**. A common electrode **310** electrically couples electrodes **102** in set **304** and permits electrical communication with all the electrodes **102** in set **304** using a single input lead to common electrode **310**. Electrode set **302** is disposed on a bottom surface **312** of insulating layer **306**, and includes a second array of linear patterned electrodes **102** that is laterally displaced from electrodes **102** on the top surface. Bottom electrode set **302** may also include a common electrode (not shown). Electrodes can be patterned on opposite sides of an insulating layer **306** to increase the ability of the electroadhesive gripping surface (end effector) **300** to withstand higher voltage differences without being limited by breakdown in the air gap between the electrodes.

Additionally or alternatively, electrodes may also be patterned on the same surface of the insulating layer, as shown in FIG. **3**B. As shown, electroadhesive gripping surface **314** comprises a sheet or flat panel with electrodes **102** patterned on one surface thereof. Electroadhesive gripping surface **314** can be substantially similar to electroadhesive gripping surface **300** of FIG. **3**A, except that electrodes sets **316** and **318** are interdigitated on the same surface **308** of a compliant insulating layer **306**. No electrodes are located on the bottom surface **312** of insulating layer **306**. This particular example shows decreasing the distance between the positive electrodes **102** in set **316** and negative electrodes **102** in set **318**, and illustrates placement of both sets of electrodes on the same surface of electroadhesive gripping surface **314**. Functionally, this eliminates the spacing between the electrodes sets **316** and **318** due to insulating layer **306**. It also eliminates the gap between one set of electrodes (previously on bottom surface **312**) and the foreign object surface when the top surface **308** adheres to the foreign object surface. Although either embodiment **300** or **314** can be used, these changes in the latter embodiment **314** may increase the electroadhesive forces between electroadhesive gripping surface **314** and the subject foreign object to be handled.

Another distinguishing feature of electroadhesive devices described herein is the option to use deformable surfaces and materials in electroadhesive device **100** as shown in FIG. **4**A-**4**C. In one example, one or more portions of electroadhesive device **100** are deformable. In a example, this includes surface **400** on device **100**, as shown in FIG. **4**B. In another example, insulating material **106** between electrodes **102** is deformable. Electroadhesive device **100** may achieve the ability to deform using material compliance (e.g., a soft material as insulating material **106**) or structural design (e.g., cilia or hair-like structures). In an example, insulating material **106** includes a bendable but not substantially elastically extendable material (for example, a thin layer of mylar). In another example, insulating material **106** may include a soft polymer with modulus less than about 10 MPa and more specifically less than about 1 MPa.

Electrodes **102** may also be compliant. Compliance for insulating material **106** and electrodes **102** may be used in any of the electroadhesive device arrangements **100** described above. Compliance in electroadhesive device **100** permits an adhering surface **400** of device **100** to conform to surface **112** features of the object it attaches to. FIG. **4**A shows a compliant electroadhesive device **100** conforming to the shape of a rough surface **112**.

Adhering surface **400** is defined as the surface of an electroadhesive device that contacts the substrate surface **112** being adhered to. The adhering surface **400** may or may not include electrodes. In one example, adhering surface **400** may include a thin and compliant protective layer that is added to protect electrodes that would otherwise be exposed. In another example, adhering surface **400** may include a material that avoids retaining debris stuck thereto (e.g., when electrostatic forces have been removed). Alternatively, adhering surface **400** may include a sticky or adhesive material to help adhesion to a wall surface or a high friction material to better prevent sliding for a given normal force.

Compliance in electroadhesive device **100** may improve adherence. When both electrodes **102** and insulating material **106** are able to deform, the adhering surface **400** may conform to the micro- and macro-contours of a rough surface **112**, both initially and dynamically after initial charge has been applied. This dynamic compliance is described in further detail with respect to FIG. **4**B. This surface electroadhesive device **100** compliance enables electrodes **102** to get closer to surface **112**, which increases the overall clamping force provided by device **100**. In some cases, electrostatic forces may drop off with distance (between electrodes and the wall surface) squared. The compliance in electroadhesive device **100**, however, permits device **100** to dynamically improve and maintain contact with surface **112**, thereby increasing the applied holding force applied by the electrodes **102**. The added compliance can also provide greater mechanical interlocking on a micro scale between surfaces **112** and **400** to increase the effective friction and inhibit sliding.

The compliance permits electroadhesive device **100** to conform to the wall surface **112** both initially and dynamically after electrical energy has been applied. This dynamic method of improving electroadhesion is shown in FIGS. **4**B and **4**C, in accordance with example embodiments. FIG. **4**B shows the surface **400** of electroadhesive device **100** initially when the device **100** is brought into contact with surface **112** of a structure with material **114**. Surface **112** may include roughness and non-uniformities on a macro, or visible, level (for example, the roughness in concrete can easily be seen) and a microscopic level (most materials).

At some time when the two are in contact as shown in FIG. **4**B, electroadhesive electrical energy is applied to electrodes **102**. This creates a force of attraction between electrodes **102** and wall surface **112**. However, initially, as a practical matter for most rough surfaces, as can be seen in FIG. **4**B, numerous gaps **402** are present between device surface **400** and wall surface **112**. The number and size of these gaps **402** affects electroadhesive clamping pressures. For example, at macro scales electrostatic clamping is inversely proportional to the square of the gap between the material **114** and the charged electrodes **102**. Also, a higher number of electrode sites allows device surface **400** to conform to more local surface roughness and thus improve overall adhesion. At micro scales, though, the increase in clamping pressures when the gap is reduced is even more dramatic. This increase is due to Paschen's law, which states that the breakdown strength of air increases dramatically across small gaps. Higher breakdown strengths and smaller gaps imply much higher electric fields and therefore much higher clamping pressures. Clamping pressures may be increased, and electroadhesion improved, by using a compliant surface **400** of electroadhesive device **100**, or an electroadhesion mechanism that conforms to the surface roughness.

When the force of attraction overcomes the compliance in electroadhesive device **100**, these compliant portions deform and portions of surface **400** move closer to surface **112**. This deformation increases the contact area between electroadhesive device **100** and wall surface **112**, increases electroadhesion clamping pressures, and provides for stronger electroadhesion between device **100** and foreign object **110**. FIG. **4**C shows the surface shape of electroadhesive device **100** and wall surface **112** after some deformation in electroadhesive device **100** due to the initial force of electrostatic attraction and compliance. Many of the gaps **402** have become smaller.

This adaptive shaping may continue. As the device surface **400** and wall surface **112** get closer, the reducing distance there between in many locations further increases electroadhesion forces, which causes many portions of electroadhesive device **100** to further deform, thus bringing even more portions of device surface **400** even closer to wall surface **112**. This increases the contact area, increases clamping pressures, and provides for stronger electroadhesion between device **100** and foreign object **110**. The electroadhesive device **100** reaches a steady state in conformity when compliance in the device prevents further deformation and device surface **400** stops deforming.

In some examples, electroadhesive device **100** may include porosity in one or more of electrodes **102**, insulating material **106** and backing **108**. Pockets of air may be trapped between surface **112** and surface **400**. These air pockets may reduce adaptive shaping. Tiny holes or porous materials for insulator **106**, backing **108**, and/or electrodes **102** allows trapped air to escape during dynamic deformation. Thus, electroadhesive device **100** may be suited for use with rough surfaces, or surfaces with macroscopic curvature or complex shape. In one example, surface **112** includes roughness greater than about 100 microns. In another example, surface **112** includes roughness greater than about 3 millimeters.

An optional backing structure **108**, such as shown in FIGS. **1**A and **4**A, can attach to insulating material **106** and include a rigid or non-extensible material. Backing layer or structure **108** can provide structural support for the compliant electroadhesive device. Backing layer **108** also permits external mechanical coupling to the electroadhesive device to permit the device to be used in larger devices.

With some electroadhesive devices **100**, softer materials may warp and deform too much under mechanical load, leading to suboptimal clamping. To mitigate these effects, electroadhesive device **100** may include a graded set of layers or materials, where one material has a low stiffness or modulus for coupling to the wall surface and a second material, attached to a first passive layer, which has a thicker and/or stiffer material. Backing structure **108** may attach to the second material stiffer material. In an example, electroadhesive device **100** included an acrylic elastomer of thickness approximately 50 microns as the softer layer and a thicker acrylic elastomer of thickness 1000 microns as the second support layer. Other thicknesses may be used.

The time it takes for the changes of FIGS. **4**B and **4**C may vary with the electroadhesive device **100** materials, electroadhesive device **100** design, the applied control signal, and magnitude of electroadhesion forces. The dynamic changes can be visually seen in some electroadhesive devices. In one example, the time it takes for device surface **400** to stop deforming can be between about 0.01 seconds and about 10 seconds. In other cases, the conformity ceasing time is between about 0.5 second and about 2 seconds.

In some examples, electroadhesion as described herein permits fast clamping and unclamping times and may be considered almost instantaneous. In one example, clamping or unclamping may be achieved in less than about 50 milliseconds. In another example, clamping or unclamping may be achieved in less than about 10 milliseconds. The response speed may be increased by several means. If the electrodes are configured with a narrower line width and closer spacing, then the response speed is increased using conductive or weakly conductive substrates because the time needed for charge to flow to establish the electroadhesive forces is reduced. Using softer, lighter, more adaptable materials in device **100** may also increase speed. It is also possible to use higher voltage to establish a given level of electroadhesive forces more quickly, and response speed can also be increased by overdriving the voltage temporarily to establish charge distributions and adaptations quickly. To increase unclamping speeds, a driving voltage that effectively reverses polarities of electrodes **102** at a constant rate may be employed. Such a voltage prevents charge from building up in substrate material **114** and thus allows faster unclamping. Alternatively, a moderately conductive material **106** can be used between the electrodes **102** to provide faster discharge times at the expense of some additional driving power required.

As the term is used herein, an electrostatic adhesion voltage refers to a voltage that produces a suitable electrostatic force to couple electroadhesive device **100** to a wall, substrate or other object. The minimum voltage needed for electroadhesive device **100** will vary with a number of factors, such as: the size of electroadhesive device **100**, the material conductivity and spacing of electrodes **102**, the insulating material **106**, the wall or object material **114**, the presence of any disturbances to electroadhesion such as dust, other particulates or moisture, the weight of any structures mechanically coupled to electroadhesive device **100**, compliance of the electroadhesive device, the dielectric and resistivity properties of the substrate, and the relevant gaps between electrodes and substrate. In one example, the electrostatic adhesion voltage includes a differential voltage between the electrodes **102** that is between about 500 volts and about 10 kilovolts. In a specific embodiment, the differential voltage is between about 2 kilovolts and about 5 kilovolts. Voltage for one electrode can be zero. Alternating positive and negative charges may also be applied to adjacent electrodes **102**.

Various additional details and examples regarding electroadhesion and applications thereof can be found at, for example, U.S. Pat. Nos. 6,586,859; 6,911,764; 6,376,971; 7,411,332; 7,551,419; 7,554,787; and 7,773,363; as well as International Patent Application No. PCT/US2011/029101;

and also U.S. patent application Ser. No. 12/762,260, each of the foregoing of which is incorporated by reference herein.

II. Active Electrostatic Cleaning

As noted above, electroadhesion can involve using compliant or flexible pads or other surfaces with one or more electrodes to achieve reversible adhesion to various foreign objects. Such arrangements can generally be used to facilitate the attachment of electroadhesive devices to wall surfaces or other substrates, as well as the picking, placement and otherwise handling of smaller foreign objects. Although the foregoing illustrations have focused primarily upon attaching an electroadhesive device to a wall or other similarly large substrate, reverse arrangements can also apply in that relatively smaller objects can be electrostatically adhered to a larger electrostatic device.

As such, the various foregoing electroadhesive concepts can generally also be applied to the cleaning or picking up of debris such as dust, leaves and other similar particles and objects. In fact, various electroadhesive sheets, pads, electrolaminate devices and other similar applications of electroadhesion have been found to interact suitably with a variety of household particles, such as dust, hair, leaves, dirt, pebbles, glass shards, crumbs, other organic matter, similar small objects and the like. Such interactions can be favorably manipulated in a controlled manner to result in a wide variety of efficient cleaning devices, systems and techniques.

Various particular applications can include indoor uses, such as a duster, broom, vacuum substitute or other household interior cleaner, for example. Other particular applications can include a variety of outdoor uses, such as a leaf collector or trash or recycling collecting system, for example. There are also many ways in which the device can be optimized for dusting and other applications involving the collection or cleaning of fine or minute particles, as set forth in greater detail below.

FIG. **5** illustrates an electroadhesive device having a plurality of smaller foreign objects adhered thereto, in accordance with an example embodiment. The electroadhesive device is presented in side cross-sectional view as a general application of a relatively larger device that can be used to adhere to smaller items. Overall environment **500** can include an electroadhesive device **502** that is configured to adhere a plurality of foreign objects **504** thereto. Any or all of foreign objects **504** can include debris such as dust, dirt, pebbles, crumbs, hair, garbage and/or a wide variety of other particulate matter. Many other items can also be adhered to the electroadhesive device **502**.

Similar to the foregoing general examples above, electroadhesive device **502** can include one or more electrodes **506** located at or near an "electroadhesive gripping surface" **508** thereof, as well as an insulating material **510** between electrodes **506** and a backing **512** or other supporting structural component. Such backing **512** may not be used in all embodiments, and the insulating material **510** and/or backing **512** can be rigid or flexible, as may be desirable for a particular application. For example, the entire electroadhesive device **502** can be a flexible sheet in some instances. For purposes of illustration, electroadhesive device **502** is shown as having eighteen electrodes in nine pairs; however, more or fewer electrodes can be used in a given electroadhesive device. Further, electrodes **506** can be spread out in more than one dimension, such as across an entire surface in two dimensions.

Also similar to the foregoing general examples, an electroadhesive force can be "felt" or experienced by each individual foreign object or particle **504** that is adhered to surface **508**. In general, a given individual particle can be more susceptible to experiencing an individual electroadhesive force where the foreign object or particle **504** is big enough to be in comparable size with and/or to span at least two oppositely charged electrodes **506**.

In some examples, various foreign objects or debris or particles **514** might be too small to be adhered effectively to the electroadhesive device **502**. This can be caused by such particles not being big enough to span across multiple electrodes **506**. Where a given particle **514** is so small that it would experience being proximate a single electrode **506**, then a resulting electroadhesive force may be minimal or nonexistent with respect to such a small foreign object or particle. Accordingly, smaller electrodes **506** and spacing between electrodes can generally result in an ability to adhere smaller foreign objects and particles **504** and **514**. Such size and spacing of electrodes **506** can be referred to as the "pitch" in an overall electrode pattern, with a smaller pitch resulting in an improved ability to adhere smaller foreign objects and particles. It should be noted that it is possible to adhere to particles that are smaller than the spacing between electrodes. For example, sand can be picked up by electrodes with a pitch of approximately 3 mm. Various design and operational considerations with respect to variable pitches can provide useful in the ability to clean and/or control differing sizes of objects and particles, as set forth in greater detail below.

FIG. **6**A illustrates an electroadhesive cleaning pad with its power supply turned off in front perspective view, in accordance with an example embodiment. Overall environment **600** can include an active electroadhesive cleaning pad that can be identical or significantly similar to foregoing electroadhesive device **502** in many regards. This active electroadhesive cleaning pad can have, for example, an interactive front surface and a plurality of electrodes (not shown) that are disposed at, proximate to, or behind the electroadhesive surface. An active power supply, such as a battery, capacitor, A/C source, or other suitable controllable power source (not shown) can supply a voltage to the electrodes in a controlled manner upon the actuation of a user input, for example. Such a user input can be made by way of a user input component, which can be a switch, button, knob, dial, or other similar component. As shown in environment **600**, no power has been applied, such that no voltage is present at the electrodes and no electroadhesive force is present at the electroadhesive surface. As would be expected, no foreign objects or particles are adhered to the electroadhesive surface as a result.

FIGS. **6**B-**6**E each illustrate in similar front perspective views the active electroadhesive cleaning pad of FIG. **6**A with its power supply turned on and various types of particulate matter or debris being adhered thereto, in accordance with example embodiments. As a first example, environment **601** in FIG. **6**B depicts how a plurality of pebbles adheres to the electroadhesive cleaning pad. FIG. **6**C shows an environment **602** where the cleaning pad has a collection of dirt adhered thereto, while FIG. **6**D shows an environment **603** where a significant amount of dust is adhered to the cleaning pad. In addition to these examples, hair, crumbs, garbage, and a wide variety of other particulate matter and foreign objects can be adhered to the cleaning pad.

FIG. **6**E depicts an environment **604** where a mixed variety of pebbles, dirt, dust and hair are all adhered to the electroadhesive cleaning pad at the same time. A robust adhesion of such particulate matter and other foreign objects to the electroadhesive pad can be achieved while the applied voltage is turned on. Such robust adhesion is sufficient to maintain the positions of the various objects and particulate matter even during a reasonable amount of shaking of or contact with the electroadhesive pad. When the voltage is removed (e.g., power is shut off) such that the various electroadhesive forces with respect to the particulate matter items is reduced or eliminated, these foreign particles and items tend to readily fall away from the electroadhesive pad. As such, control of the applied voltage can result in significant control of the various particulate matter and other foreign objects adhered to the electroadhesive pad, device or system.

In examples, the electroadhesive cleaning pads depicted in FIG. **6**A-**6**E could be used as a hand duster or a feather duster. For instance, a hand duster may include a handle coupled to the electroadhesive cleaning pad. The hand duster may be applied directly to a surface of any type (wood, ceramic or any surface) to be cleaned by, for example, swiping the electroadhesive cleaning pad across the surface to be cleaned. In some examples, the hand duster may not include a handle, and the electroadhesive cleaning pad can be held by a hand of a user and swiped over the surface to be cleaned to remove any debris thereon. In examples, the electroadhesive cleaning pads can be made into feather-like shapes for use as a feather duster. Or, electroadhesive cleaning means can be coupled to preexisting feathers of the feather duster. A feather duster may include a wooden handle (or a handle made of any other material) coupled to feathers that are wound onto the handle by a wrapped wire, for example. In some example, the dusters may have retractable casing instead of the handle. Flexible feathers, and electroadhesive cleaning means coupled thereto, allow the duster to reach place that are difficult to reach by other types of dusters.

It should be noted that in some examples the electroadhesive cleaning pad may be configured to adhere to, or comply with a shape of, the surface to be cleaned. However, in other examples, the electroadhesive cleaning pad may be configured to adhere to debris (e.g., dust, dirt, pebbles, etc.) without adhering to the surface to be cleaned. Still in other examples, the electroadhesive cleaning pad may be configured to adhere partially to the surface to be cleaned and partially to the debris to be removed from the surface to be cleaned.

Depending on the various specific effects desired, the material or materials used for the electroadhesive surface could be varied. The electroadhesive surface material could be soft and tacky in nature, such as in the form of soft polyurethanes or silicones, whereby additional passive adhesion forces could be created. Alternatively, more slippery surfaces could be used for the electroadhesive surface material, such that the surface could be more easily cleaned. Such slippery surface materials could include one or more sheets of polyurethane, for example. Other types of materials could also be used to form all or portions of the electroadhesive surface, as may be desired, and such other materials can include various fabrics, fibers, cloth, plastics, etc.

In addition to the types of materials used, various shapes, arrangements and configurations of the electroadhesive surface or surfaces can also affect the amount of compliance between the electroadhesive surface and the various foreign objects and particulate matter to be cleaned. For example, when picking up relatively dried out and flat leaves that have a complex shape, flexibility of the electroadhesive surface may improve electroadhesion. As such, thin sheets that flexibly drape around relatively thin, larger and complex foreign objects, such as dried leaves, can be useful for these particularized applications. When picking up very small objects on a flat electroadhesive surface, or when picking up fresh and pliable leaves, however, an electroadhesive pad having a more rigid backing has been found to be adequate. Compliance can also be achieved through structural means such as cilia, flaps and/or other similar features on the electroadhesive surface. As such, an overall larger pad or other electroadhesive cleaning device can include a relatively stiff backing coupled with numerous smaller hairs or flaps on the electroadhesive surface itself to provide the compliance necessary to conform around the foreign objects to be cleaned. Such features can resemble the bristles or fibers found in common cleaning implements such as mops, brooms, brushes, dusters and the like, for a combined mechanical and electroadhesive cleaning of foreign objects.

FIG. **7**A illustrates an electroadhesive cleaning device having bristles or cilia along its electroadhesive surface shown in side elevation view, in accordance with an example embodiment. As shown, environment **700** includes a plurality of foreign objects **702** that are dispersed about ground or floor surface **704**. An active electroadhesive cleaning device **706** can include a variety of components that are fronted by an electroadhesive surface **708** that is configured to interact with the various foreign objects **702**. One or more hairs or cilia **710** can be dispersed about electroadhesive surface **708** to aid in the compliance and adherence of the foreign objects **702** to the electroadhesive surface.

One or more electrodes (not shown) disposed behind or otherwise located proximate to the electroadhesive surface can also be used to generate electroadhesive forces with respect to each of foreign objects **702** when the electroadhesive surface **708** contacts the foreign objects **702** or is placed in reasonably close proximity thereto. As noted above, the cilia **710** and/or one or more other features located at or about the electroadhesive surface **708** can result in a deformable surface or surface region, such that the deformable surface portion can move closer to a respective foreign object **702** when the electroadhesive force is applied thereto.

FIG. **7**B illustrates in side elevation view another compliance example in the form of an active electroadhesive cleaning device having a plurality of extendable flaps along its electroadhesive surface, in accordance with an example embodiment. Alternative environment **712** can include the same or substantially similar particulate matter or foreign objects **702** along the ground or another floor surface **704**. A similar active electroadhesive cleaning device **706** can have an electroadhesive surface **708** to be placed proximate the foreign objects to be cleaned, as in the foregoing embodiment. Instead of (or in addition to) cilia, however, the electroadhesive surface **708** in environment **700** can include a plurality of flaps **714** that are partially coupled to and extendable from the electroadhesive surface. Such flaps can be adapted to carry electroadhesive charge, similar to the foregoing electroadhesive surfaces, but are much more flexible and compliant with respect to contacting the foreign objects to be cleaned.

Another feature that can be used effectively to control and manipulate particulate matter and other foreign objects to be cleaned can involve the use of patterned electrodes. As noted above, finer electrode patterns may be more optimal for smaller sized particles, such that each individual particle "feels" the electrical field across a plurality of oppositely charged electrodes, in contrast to being subject to a single electrode and thus typically a single polarity. Larger electrode patterns may interact with correspondingly larger or more conductive objects, such as leaves or larger trash items, for example. By designing electrode patterns appropriately, it is possible to tune what types of objects can be carried or otherwise manipulated for cleaning. It is also possible to have a relatively fine electrode pattern where changing the connectivity or addressing appropriate electrode regions can tune the electroadhesion to the sized objects of interest. Thus, electroadhesion can be used not only as a general cleaner but also as a specific cleaner to separate out certain object or debris sizes or materials from others that may be present on a surface to be cleaned. This concept is illustrated with respect to FIGS. **8**A through **9**C.

FIG. **8**A illustrates a checkerboard type electrode pattern for use with respect to a suitable electroadhesive surface shown in top plan view, in accordance with an example embodiment. A suitable power source, one or more user input devices or components, electroadhesive surface(s) and other components can be used in conjunction with the electrodes shown in electrode pattern **800**, but that such items are not displayed here for purposes of simplicity in illustration and discussion.

Electrode pattern **800** can involve a checkerboard arrangement of alternating positively and negatively charged regions. This can be accomplished, for example, by alternating positive and negative charges across each of the electrodes in the pattern. As shown, electrode **802** can be positively charged, while adjacent electrode **804** can be negatively charged. This alternating charged pattern can continue in two dimensions across the entire electrode pattern **800**. Where this is done at the individual electrode level, as in pattern **800**, then the smallest pitch possible for that pattern can be observed. That is, pattern **800** is configured such that it will be able to attract the smallest foreign objects that it possibly can. Such smallest foreign objects possible might generally be about the size of one electrode given the simple geometry of this particular pattern.

FIG. **8**B illustrates the checkerboard type electrode pattern of FIG. **8**A having an alternatively charged configuration in top plan view, in accordance with an example embodiment. Alternatively configured electrode pattern **806** is notably formed on the same electrodes and components as pattern **800** is. That is, the same 64 electrodes may be used to form pattern **800** and alternative pattern **806**. Unlike the finer pitch 64 alternating region pattern **800**, the alternative pattern **806** is configured such that there are 4 alternating regions. This can be done by manipulating the charges at some of the electrodes such that an effectively larger pitch is created. For example, while the charge on electrode **802** stays the same, the adjacent electrode **808** (replacing electrode **802**) has had its charge switched from negative to positive. Similar charge switches to various other electrodes in the 64 electrode pattern have also been made to achieve the simpler four region result.

A variety of other electrode patterns can alternatively be achieved by manipulating the charge to each of the electrodes in a similar manner. For example, a 4×4 pattern can similarly be achieved, in addition to the 8×8 and 2×2 patterns shown in FIGS. **8**A and **8**B. Alternatively, other patterns such as 4×2, 1×1, and 2×1 can also be configured. Further, the number of electrodes or effective electrode regions is not limited to 64, and can be smaller than or substantially greater than this number. As such, numerous possible electrode arrangements are possible, with many such arrangements being configurable to numerous different electrode patterns. Such different electrode patterns can also have differing pitches.

FIGS. **9**A-**9**D illustrate a more complex example of electrode patterns involving interdigitated electrode arrangements, in accordance with example embodiments. Starting with FIG. **9**A, an example interdigitated electrode pattern of straight stripes for use with respect to a suitable electroadhesive surface is similarly shown in top plan view. The electrode pattern is being illustrated for purposes of simplicity. As shown in electrode pattern or arrangement **900**, two electrodes **902** and **904** are present. Electrode **902** can be positively charged, while electrode **904** can be negatively charged, and the polarities of both electrodes can be reversible, as may be desired.

Electrodes **902** and **904** are interdigitated, such that numerous different regions for electroadhesive forces to form can be observed from just these two electrodes. Due to the particular geometry of electrodes **902** and **904**, the pitch for this particular patterned arrangement would effectively be the width of an interdigitated "finger" in many instances. In the event that these fingers are relatively narrow then, the size of debris or particulate matter or other foreign objects that can be adhered to or otherwise handled by an electroadhesive cleaning device or system using patterned arrangement **900** would be relatively small.

FIG. **9**B illustrates in top plan view an interdigitated electrode pattern of diagonal stripes for use with respect to a suitable electroadhesive surface, in accordance with an example embodiment. The electrodes pattern shown in FIG. **9**B is similar to the pattern shown in FIG. **9**A, but the "fingers" or interdigitated electrodes are slanted to form diagonal stripes. Different angles can be used. Also, the straight stripes depicted in FIG. **9**A and the diagonal stripes depicted in FIG. **9**B are examples for illustration only, and any other pattern can be used.

FIG. **9**C similarly illustrates in top plan view an example interdigitated electrode pattern incorporating multiple repetitions of the pattern in FIG. **9**A, in accordance with an example embodiment. Overall electrode pattern **906** includes six repeated instances or copies of pattern **900** from FIG. **9**A. These "copies" of pattern **900** are effectively interdigitated within each other, and are then connected by common buses or connectors **908**. Each such common bus or connector **908** can be used to couple like charged regions on a subset of the six repeated copies of pattern **900**, such as on half of the repeated copies. In this particular example, each connector **908** can be arranged to connect similarly chargeable regions on alternating "fingers" **900** of overall pattern **906**. That is, a single connector **908** would connect the positively (or alternatively negatively) charged regions of the first, third and fifth sub-patterns **900** within overall pattern **906**. Similar connections **908** could then be made with respect to the second, fourth and sixth sub-patterns respectively.

When connected in this overall manner by connectors **908**, the overall pattern **906** can then be manipulated to alter the observable pitch of the pattern. For a finer pitch, for example, all positive and negative electrode regions can be charged as shown at the finest possible levels across the entire pattern **906**. For a larger pitch though, all of the interconnected regions on the first, third and fifth sub-patterns **900** can all be set to the same positive or negative charge, while all of the interconnected regions on the second, fourth and sixth sub-patterns **900** can all be set to the same charge that is opposite those of the other three sub-patterns. For example, the entirety of the first, third and fifth sub-patterns **900** can be positive, while the entirety of the second, fourth and sixth sub-patterns can be negative. This then results in a larger overall pitch for a result that would then tend to ignore particles of a size greater than the width of a single finger of electrode **902** but smaller than the overall width of the sub-pattern **900**.

FIG. **9**D extrapolates this concept into yet a further extended electrode pattern incorporating multiple repetitions of the pattern in FIG. **9**C. As shown, overall electrode pattern **910** can be disposed behind or proximate an electroadhesive surface **912** of an electroadhesive cleaning device. A plurality of sub-patterns **906** that correspond to the overall pattern shown in FIG. **9**C are provided in an interdigitated pattern themselves across overall electrode pattern **910** in multiple directions. Further common buses or connectors can be formed between each of the sub-patterns **906** such that additional control can be had with respect to designating the pitch on overall pattern **910**. Further iterations of this process can also be implemented so as to add further control over designating pitch sizes. FIGS. **9**C and **9**D depict repetitions of the electrodes pattern shown in FIG. **9**A as an example for illustration only, and the electrode pattern of diagonal stripes shown in FIG. **9**B, or any other pattern, could be used as well.

FIG. **10**A illustrates a track-based electroadhesive cleaning device **1000**, in accordance with an example embodiment. The device **1000** may include components such as a handle grip **1002**, an adjustable-height handle **1004**, and cleaning head **1006**. These are example components for illustration and many other components can be included in the electroadhesive cleaning device **1000** configuration shown in FIG. **10**A.

FIG. **10**B illustrates a zoomed-in view of the track configuration for the electroadhesive cleaning device in FIG. **10**A, in accordance with an example embodiment. FIG. **10**B depicts components housed inside the cleaning head **1006** such as two rollers **1008**A and **1008**B and an electroadhesive pad **1010** covered by a belt **1012**. The belt **1012** can include, for example, a thin plastic sheet that covers the electroadhesive pad **1010**. The handle **1004** may include means (e.g., a button dial, knob, etc.) for controlling and/or modifying an input voltage that is applied to electrodes of the electroadhesive pad **1010**. As the electroadhesive cleaning device **1000** is pushed forward or backward (e.g., using the handle **1004**) on a surface having debris thereon, the electroadhesive pad **1010** rotates with the roller **1008**A and causes the debris to electrostatically adhere to the belt **1012**. Further, the electroadhesive cleaning device **1000** may include a scraper **1014** positioned close to or in contact with the belt **1012**. As the belt **1012** rotates with the motion of the electroadhesive cleaning device **1000**, the scraper **1014** may be configured to remove any debris adhered to the belt **1012** so as to clean the belt **1012**. The roller **1008**A can be configured to roll forwards or backwards relative to the motion of the cleaning device **1000**, or the roller **1008**A can be allowed to passively rotate with the contact friction from the surface to be cleaned.

FIG. **10**C illustrates portion of an alternative track-based electroadhesive cleaning device, in accordance with an example embodiment. In the arrangement depicted in FIG. **10**C, the belt **1012** rotates over a stationary electroadhesive pad **1016** (including the electrodes). The belt **1012** includes no electrodes. Neither the electroadhesive pad **1016** nor the electrodes therein rotate with the belt **1012**. In some examples, this configuration shown in FIG. **10**C may improve debris removal from the belt **1012** (by a scraper such as the scraper **1014**, for example). Debris attached to a portion of the belt **1012** close to the electroadhesive pad **1016** may be strongly attached to the belt **1012**. As the belt **1012** rotates away from the electroadhesive pad **1016**, the debris is less strongly attached to the belt **1012** and is easier to remove.

FIG. **10**D illustrates in side perspective view the track-based electroadhesive cleaning device **1000** cleaning a surface **1018**, in accordance with an example embodiment. Track-based electroadhesive cleaning device **1000** can be configured to move across and clean debris or foreign objects **1020** from ground or floor surface **1018**. In addition to having a power supply or source, input component(s), and various electrodes similar to those described in greater detail above, cleaning device **1000** also includes a number of additional features. The handle **1004** can be provided for a user to manually operate or manipulate the overall device **1000**, such as in a forward motion (indicated by the arrow) across surface **1018**. In some examples, the cleaning head **1006** may be configured to house one or more rollers (e.g., **1008**A and **1008**B) and additionally a power supply, such as battery, driving electronics, such as high voltage DC-DC converters, other pertinent switches and circuitry. The cleaning head **1006** may also contain an electric motor to actively drive the rotation of the belt **1012** or a mechanical transmission to drive the roller rotation at a particular speed and/or direction relative to the travel direction of the cleaning head **1006** over the surface **1018**.

The electroadhesive surface can be configured in the form of a continuous loop or track situated across one or more rollers **1008**A and **1008**B, and the various electrodes (not shown) can be arranged in a pattern behind or adjacent to the electroadhesive surface. As the device **1000** moves across surface **1018**, voltage is applied at the electrodes proximate the portion of the electroadhesive surface beneath the device, such that particulate matter and/or foreign objects **1020** on the foreign surface **1018** are adhered to that portion of the electroadhesive surface that is beneath the device **1000** and has electroadhesive forces being conducted therethrough.

As the tracked electroadhesive surface or belt **1012** departs foreign surface **1018** at the front side of the device **1000** during the motion of the device **1000**, at least some of the foreign objects **1020** can remain adhered to the belt **1012** and are thus carried up and away from the surface **1018** and across the upper tracked portion of the device **1000** accordingly.

FIG. **10**E illustrates in side perspective view an alternative track-based electroadhesive cleaning device **1022** having ion charge sprayers **1024**, in accordance with an example embodiment. Alternative track-based electroadhesive cleaning device or system **1022** can be similar to the foregoing device **1000** in a number of respects. In addition to having an identical or similar handle, rollers, and continuous tracked electroadhesive surface, the device or system **1022** can also include one or more ion charge sprayers **1024**. Such ion charge sprayer(s) **1024** can spray or otherwise disperse ionic charges in front of the cleaning device or system **1022**.

In this arrangement or system, a respective electroadhesive surface, sheet, or belt might have one electrode associated therewith, with such a single electrode being only positively or negatively charged. As such, the sprayed ionic charges can be of the opposite polarity from the single charge across the tracked electroadhesive surface or belt. For example, the ion charge sprayers **1024** can spray negative charges on foreign dust particles, while the electroadhesive surface would be charged positively such that it picks up all of the now affirmatively negatively charged dust particles. One advantage of this embodiment is that the polarity of the charge on the dust or debris particles and other foreign objects **1020** to be cleaned can be accurately predicted, since specific ion charges to that effect are being sprayed. As such, the electroadhesive surface can be simpler in that it might require a single electrode of a polarity that is opposite to the sprayed charge.

In these particular tracked electroadhesive cleaning device examples, as well as in various other examples, several additional device and system aspects can apply. For example, the magnitude of voltage on an electroadhesive clamping component or components can be varied to pick up various specifically targeted objects, such as by size and/or weight. Such targeting can also be accomplished by using a patterned electrode arrangement with variable pitches, as detailed above.

It is also contemplated that alternating the polarity of the electroadhesive clamping components can provide several advantages. For example, the particles or other foreign objects are less likely to become damaged or disadvantageously charged up themselves when first clamped and then released, such as by reducing, shutting off or reversing the polarity of the applied charge. In some cases, it may be possible to use this phenomenon to disperse or repel the particles or foreign objects away from the electroadhesive surface in a desirable or otherwise controllable manner. Where a direct current pulse is used, for example, a negative polarity pulse for a short duration can helps with the prompt release or repelling of dirt and other foreign objects from the electroadhesive surface.

In various examples, the disclosed electroadhesive cleaning devices and systems can employ a mechanical means of releasing the dust or other foreign objects more fully when the voltage is at different stages, such as fully on, reduced, switched off, or even reversed. Some approaches in helping to remove particles and foreign objects from the electroadhesive surface can include jolting the device, such as with an electromagnetic solenoid, for example, vibrating the device, such as with an electromagnetic coil or embedded electroactive polymer device, for example, or the use of an air or water jet that is squirted parallel to the face of the electroadhesive surface. Since reducing or switching off the input voltage often does not often result in a full release of particles, and especially lighter particles such as dust, it may be desirable to use a mechanical wiper or brush to help clean or recycle the electroadhesive surface.

One way to do this continuously is in continuous tracked or a roller embodiment. The electroadhesive surface can be in the form of an electroadhesive track or belt that can have several distinct patterns or sections along its length. In such an arrangement, a front roller, which can be non-rotating and has the electrodes coupled thereon, can be used to charge the electroadhesive surface as it begins to contact the foreign surface to be cleaned, and a rear roller can be used to discharge the electroadhesive surface or belt after the surface and adhered foreign objects rotate up and away from the foreign surface being cleaned. In some examples, electroadhesion electronics can be mounted fully inside front and/or back rollers. Other types of electroadhesive surfaces can also be employed for such cleaning purposes, including "flattened tire" and "wheels with flap" designs, such as those described in U.S. Pat. No. 7,554,787, which is incorporated herein by reference.

FIG. **10**F illustrates a cleaning arrangement for a track-based electroadhesive cleaning device, in accordance with an example embodiment. The cleaning arrangement depicted in FIG. **10**F may be referred to as a "self-cleaning" arrangement that can be implemented for any of the forgoing electroadhesive devices described above. FIG. **10**F depicts a track-based electroadhesive device **1025** including three rollers **1026**A, **1026**B, and **1026**C; however, a greater or fewer number of rollers can be used. One or more of the roller may be powered by, for example, an electric motor to drive the device **1025**. The device **1025** also includes an electroadhesive pad **1028**, a belt or thin sheet **1030** (can be made of a dielectric material, for example), a scraper **1032**, and a brush **1034**. As the device **1025** moves over or across a surface **1036** to be cleaned, when voltage is applied to the electroadhesive pad **1028**, debris on the surface **1036** may be electroadhesively attached to the belt **1030**. As the belt **1030** moves, or rotates, away from the surface **1036**, the scraper **1032** removes the debris adhered to the belt **1030**. Further, if not all the debris is removed from the belt **1030** by the scraper **1032**, the brush **1034** may be configured to remove some of the debris that remained attached to the belt **1030**. In some examples, the scraper **1032** may be used without the brush **1034**, and in other examples, the brush **1034** may be used without the scraper **1032** for cleaning the belt **1030**. The arrangement shown in FIG. **10**F is an example for illustration and different arrangements can be used with different components can be implemented to clean the belt **1030** and/or the pad **1028**. For instance, instead of using the brush **1034**, a sponge can be used instead to clean the belt **1030**. Other examples are possible.

In examples, the electroadhesive pad **1028** may be non-rotating (i.e., locked) and the rollers **1026**A and **1026**B may be locked. In these examples, to clean the belt **1030** and/or the pad **1028**, the rollers **1026**A and **1026**B may be quickly spun to perform a cleaning cycle by causing the belt **1030** and the pad **1028** to rotate and thus causing the scraper **1032** and/or brush **1034** to remove debris adhered to the belt **1030** and/or pad **1028**.

FIG. **10**G illustrates the electroadhesive cleaning device having a tray to collect debris, in accordance with an example embodiment. For example, as a scraper and/or brush cleans a belt of an electroadhesive cleaning device by removing debris attached to the belt, the debris removed can be collected in a tray. FIG. **10**G depicts a tray **1038** (e.g., a dustbin or other receptacle) that can be assembled into, and removed from, the cleaning head **1006**. As a given cleaning mechanism (e.g., a scraper and/or a brush) removes dirt adhered to the belt, the removed dirt can be collected in the tray **1038**, which can later be removed to be cleaned and reinstalled into the cleaning head **1006**. In such embodiments where a belt is configured to rotate over an electroadhesive pad, the electroadhesive pad is generally not contacting debris over the surface to be cleaned, and thus may not require cleaning. The belt requires cleaning and may be a removable part that can be replaced overtime without having to replace the electroadhesive pad.

Thus, electroadhesive surfaces such as the electroadhesive pads shown in FIGS. **6**A-**6**E and the continuous electroadhesive belt or track described with respect to FIGS. **10**A-**10**G can be treated as a consumable or disposable that can be changed after several cleaning operations. In some examples, many thin layer pads or tracks can be stacked on top of each other, such that a user can simply peel off and dispose of the outermost pad or track layer when it gets too old, damaged or dirty. In such instances, due care should be taken to ensure that the electric field produced by the electroadhesive pad sufficiently penetrates through the material of the track or belt, even in its thickest configuration, such that the electroadhesion forces are present on the surface of the track or belt.

FIG. **10**H illustrates a back view **1040** of a track-based electroadhesive cleaning device, in accordance with an example embodiment; and FIG. **10**I illustrates a modular track-based electroadhesive cleaning device with the tray and a replaceable belt or replaceable roller, in accordance with an example embodiment. The back view **1040** depicts a button **1042** (with a spring mechanism) that, when pressed, opens the cleaning head **1006** to facilitate belt **1012** or electroadhesive pad **1010** removal or replacement. The modular design shown in FIG. **10**I also depicts the tray **1038** that can be removed and reinstalled within the cleaning head **1006**. Such modular design facilitates removal and replacement of the belt and/or electroadhesive pad after several cleaning operations and considering the belt and/or pad as consumable or disposable items. In examples where a belt is configured to rotate over an electroadhesive pad and the electroadhesive pad does not contact debris over the surface to be cleaned, only the belt may be replaceable, and the electroadhesive pad does not need to be replaced.

Other types of cleaning devices are also envisioned in addition to the foregoing examples. For example, a rolling device with an embedded motor can be configured to move on its own, similar to commercially available self-propelled vacuum cleaning robots. A wall climbing robot, for example, can clean a foreign surface as it climbs the surface and possibly does other operations, such as inspection. Flat active electroadhesive cleaning pads similar to those shown in FIGS. **6**A-**6**E can be used as cleaning patches in applications where rolling motion is either unnecessary or undesirable. A significantly large active electroadhesive cleaning pad can be configured to be removable wallpaper (e.g., transparent, plain colored or decorative) that effectively lines the inside of a room, for example. As dust or pollen and other allergens move around inside the room due to Brownian motion, such particles may stick to the active electroadhesive cleaning wall paper. Periodically, a user can simply switch off the active electroadhesion and wipe the wallpaper with a separate conventional cleaning device, such as a cloth. Electroadhesion also allows conformability, and lends itself to wearable devices, such as a mask or respirator device or embedded into clothes. In such cases, electroadhesion can act to trap dust on its own, which may be in addition to filters that can be woven into fabrics and/or other materials comprising the mask.

FIG. **11**A illustrates an alternative arrangement for an electroadhesive cleaning device, in accordance with an example embodiment. FIG. **11**A depicts the electroadhesive cleaning device having a short handle **1102** suitable for cleaning walls, for example. However, in other examples, a longer handle can be used and the electroadhesive cleaning device can be used to clean any type of surface. The electroadhesive cleaning device may include a single roller **1104**. The roller **1104** may include an electroadhesive pad **1106** (having electrodes embedded therein, for example) on a compliant backing **1108**. The roller **1104** may include more than one pad per roller in some examples. The roller **1104** may, in some examples, be made of double shell design having a first shell **1110**A and a second shell **1110**B to facilitate keeping any conductive material inside the roller **1104** for safety, i.e., all the electrical connections can be made internal to the roller. An adhesive film can be used at seam **1112** for stress relief and to maintain a circular cross section for the roller **1104**, for example. FIG. **11**A depicts a modular design for the electroadhesive cleaning device **1100** where the roller **1104** can be easily removed and replaced with a new roller when needed.

FIG. **11**B illustrates a scraper **1114** in contact with the roller **1104** to remove debris **1116** removed during rotation of the roller **1104**, in accordance with an example embodiment. The scraper **1114** is depicted resting against the electroadhesive surface of the roller **1104**. The scraper **1114** may be configured to, as the roller **1104** rotates, remove at least a portion of the debris **1116** adhered against the electroadhesive surface of the roller **1104**. The scraper **1114** can be configured to rest on the electroadhesive surface of the roller **1104** at such an angle that is effective to enable the scraper **1114** to remove debris in both directions of travel of the roller **1104**.

FIG. **11**C illustrates a back view of the electroadhesive cleaning device shown in FIG. **11**A showing a spring-loaded scraper **1114**, in accordance with an example embodiment. FIG. **11**C depicts a spring **1118** loading or pushing against the scraper **1114** such that the scraper **1114** maintains contact with roller **1104** to effectively remove the debris **1116**. Spring loading is just one example, as other mechanical means could be used to maintain contact between the scraper **1114** and the roller **1104**.

FIG. **12** illustrates various arrangements depicting respective rotational configurations for roller-based and track-based electroadhesive cleaning devices, in accordance with example embodiments. Arrangement **1** depicts a roller-based electroadhesive cleaning device having a roller **1202**. The roller may include or be coupled to electroadhesive pads and electrodes as described in the foregoing examples (e.g., description with respect to FIGS. **11**A-**11**C), and may also include a soft foam backing or other type of compliant backing. In arrangement **1**, the roller **1202** rotates in the same direction of travel (i.e., rolling along a surface to be cleaned). Arrangement **2** is similar to arrangement **1** except that the roller **1202** is rolling in a reverse direction. By driving the electroadhesive roller backwards relative to the direction of travel of the electroadhesive device on the surface to be cleaned, debris pickup rate may increase. The improvement in debris pick relative to arrangement **1** may be more prominent when the surface has more than one layer of dirt of debris thereon.

Arrangement **3** depicts an electroadhesive cleaning device similar to the electroadhesive cleaning device shown in FIG. **10**C. The electroadhesive cleaning device in arrangement **3** includes a sheet belt **1204** wrapped around a stationary electroadhesive pad **1206** that can comprise electrodes that produce electroadhesion forces when a voltage is applied thereto. As described with respect to FIG. **10**C, arrangement **3** may facilitate removing debris adhered to the belt **1204**. In Arrangement **3** the belt **1204** is rolling backwards relative to the direction of travel of the electroadhesive device on the surface to be cleaned to improve debris pick up as described in arrangement **2**.

Arrangement **4** depicts the sheet belt **1204** wrapped around the roller **1202**. In this arrangement, both the belt and the roller may be rotating, or the roller may be stationary while the belt is rotating. In this example, the belt **1204** is rotating backwards relative to the direction of travel of the electroadhesive device on the surface to be cleaned to improve pick up. Arrangement **5** depicts a scraper **1208** added to arrangement **4**. The scraper may be similar, for example, to the scraper **1114** shown in FIG. **11**B or the scraper **1032** shown in FIG. **10**F, and may be configured to remove debris attached to the belt. It is noted that arrangement **5** shows that the belt is configured to rotate in the same direction regardless of the direction of travel of the cleaning device. Thus, for direction of travel **1**, the belt is rotating backwards; for direction of travel **2**, the belt rotation does not change (e.g., roll along the surface to be cleaned). Arrangement **6** is similar to arrangement **5**, but the belt is configured to change direction of rotation when the direction of travel of the electroadhesive cleaning device changes. The belt thus rotates backwards relative to the direction of travel regardless of the direction of travel.

As shown in FIG. **12**, in some cases, a track-based cleaning device may include electrodes coupled to or embedded within, and thus rotating with, the track or belt. However, in other cases, the rotating tack or belt may include a sheet of dielectric material (e.g., a polymer material) that rotates over stationary electrodes; thus, the track or belt rotates relative to the stationary electrodes.

The configurations and arrangements shown in FIG. **12** are examples included for purposes of illustration. Other configurations or combinations of features and arrangements are possible as well. The rotation of rollers or belts may result from rolling on a surface to be cleaned, or the device may be powered (e.g., by an electric motor) that causes the rollers and/or belt to rotate.

Power for a given active electroadhesive cleaning device may come from a battery, capacitor or other storage device, for example. In some cases, the power can be generated by the motion of the cleaning device itself, similar to what is used in a Van de Graaf generator, for example. In some cases, it may also be possible to generate the required charges from the triboelectric effect of rubbing the cleaning device against the surface of interest, or internally against the body of the cleaning device. For example, such a result can be obtained where an electroadhesive surface in the form on an electroadhesion belt or track is driven forward. Where a given electroadhesive surface is desired to be used in a back and forth motion (e.g., as with typical household vacuum cleaners and carpet sweepers), the surface of the electroadhesive track or belt that is in contact with the surface to be cleaned can be kept at a high voltage, while the top surface of the track that is away from the surface to be cleaned can be held at ground potential. This can permit the active electroadhesive cleaning device to clean the target surface regardless of the direction of movement of the electroadhesive track. In such embodiments, the collecting belt or other similar component that collects charges from rotating around a roller or other similar component formed from a dissimilar material can be considered an input component for the device or system.

FIG. **13** illustrates an arrangement depicting a battery **1302** powering an electroadhesive cleaning device, in accordance with an example embodiment. The electroadhesive device includes rollers or wheels **1304**A and **1304**B for travel in both directions. The device also includes rollers **1306**A and **1306**B that can be used for rotating a belt or electroadhesive pad **1308**. In some examples, the electroadhesive pad may be coupled to the roller **1306**A separate from the belt **1308**. Electrodes can be embedded in the belt **1308** or in the roller **1306**A, for example. Other examples are possible. Electronics used to for operating the electroadhesive cleaning device depicted in FIG. **13** may be embedded within one or more of the rollers **1306**A and **1306**B. The device also includes a spring-scraper mechanism **1310** to clean debris adhered to the belt **1308**. The scraper can be configured to have an angle that facilitates debris removal in both directions of travel of the device. The debris cleaned by the mechanism **1310** can be collected in a tray **1312** having a lip **1314** to prevent spilling.

The battery **1302** may be configured to power the device and any electronics configured to drive different functions of the cleaning device. Additionally, as shown in FIG. **13**, the battery **1302** may be configured to be a counterweight that stabilizes the electroadhesive cleaning device.

As yet another possible feature, an added ability to sense dust, dirt or other foreign particles or items can be helpful. Such sensing can be accomplished by way of measuring the capacitance and/or resistance at one or more locations on the interactive or electrode surface. Changes in the capacitance and/or resistance can indicate that there is too much dirt or particulate matter on the electroadhesive surface. Such a sensed result can be acted upon in a number of ways. An alarm in the form of an indicator light or sound can let the user know that the surface may need to be cleaned or replaced. Alternatively, or in addition, sensing an increased amount of dirt or particulate matter can result in an automated response to repel the dirt, such as by way of a reversed polarity burst or pulse. The level or repetition of the burst or pulse can be increased as may be desirable in response to a sensed increase in dirtiness on the surface. In addition, sensing can be used to discriminate between different types of materials and/or different sizes of materials to be cleaned or manipulated.

The foregoing examples of electroadhesive devices described above depict a single roller or two rollers where one of them may be touching the surface to be cleaned while the other roller does not. However, in some examples, an electroadhesive device may include two or more rollers, each touching, and removing debris from, the surface to be cleaned.

FIG. **14**A illustrates an electroadhesive cleaning device **1400** having two rollers, in accordance with an example embodiment. FIG. **14**A also illustrates an exploded view of a portion of contents of a cleaning head **1402** of the electroadhesive cleaning device **1400**. The cleaning head **1402** includes an electroadhesive power module **1404** that may include a battery. The cleaning head **1402** also may include dual rollers **1406**A and **1406**B having electroadhesive surfaces coupled thereon. The electroadhesive surfaces may include or be proximate to electrodes that are powered by the power module **1404**. In other examples, more rollers can be used. The cleaning head **1404** may also include a dust scraper and debris collection tray **1408**.

FIG. **14**B illustrates another view of the rollers illustrated in FIG. **14**A, in accordance with an example embodiment. FIG. **14**B depicts a view that shows scrapers **1410** that may be configured to remove debris attached to the electroadhesive surfaces of the rollers **1406**A and **1406**B. The debris removed can be collected at tray **1412**. Flaps **1413**A coupled to the roller **1406**A, and flaps **1413**B coupled to the roller **1406**B may function similar to the flaps **714** described with respect to FIG. **7**B, for example.

FIG. **14**C illustrates an electroadhesive cleaning device having two rollers rotating in opposite directions, in accordance with an example embodiment. FIG. **14**C also shows an example direction of travel of the device **1400**. In some examples, the two rollers **1406**A and **1406**B may rotate in the same direction (e.g., clockwise). However, as shown in FIG. **14**C, the two rollers **1406**A and **1406**B may be configured to rotate in opposite directions. In the example shown in FIG. **14**C, the front roller **1406**A is forward rolling. This roller **1406**A may be configured to be used for flattening and breaking up bigger particles of debris being picked up by the electroadhesive cleaning device **1400**. The roller **1406**B in reverse rolling may then pick up the flattened and/or broken particles. Thus, a dual roller configuration may improve debris pick up performance and may facilitate picking up or removing particles of different sizes from a surface to be cleaned. Also, debris particles **1414** may accumulate in a gap between the rollers **1406**A and **1406**B. As more dirt particles accumulate, the particles are pushed against the rollers **1406**A and **1406**B increasing pick up performance.

The foregoing examples illustrated electroadhesive cleaning devices in an arrangement that resembles a household cleaner (e.g., a vacuum cleaner). However, the electroadhesive cleaning device described herein can also be used in alternative arrangements and configurations. For example, electroadhesion cleaning can be applied in an industrial plant to clean objects before processing the objects or before applying a manufacturing process on the objects.

FIG. **15** illustrates a separate conveyor belt based electroadhesive cleaning system in side elevation view, in accordance with an example embodiment. This depicted active electroadhesive cleaning system **1502** can include an electroadhesively charged conveyor belt **1504** that processes along a plurality of rollers **1506** or other similar components. This conveyor belt **1504** can include an upper surface that is effectively the electroadhesive surface of the system, as well as a plurality of electrodes (not shown) that can be patterned beneath or otherwise proximate to the belt.

As a given foreign object **1508**A that is covered in dirt or dust encounters the electroadhesively charged belt **1504**, this foreign object **1508**A is cleaned through an electroadhesive process as it jumbles on and travel along the belt. Such a cleaning can be effected by way of, for example, a pulsed electroadhesive force that is applied all along the belt as the foreign object travels therealong. While foreign object **1508**A is significantly dirty or dusty when it first encounters the electroadhesively charged conveyor belt **1504** at the left side as shown, some of the dirt or dust is removed from the foreign object **1508**B at a partial location along the belt. In some examples, all or a substantial portion of the dirt or dust is removed from foreign object **1508**C by the time it reaches the end of travel along belt **1504**. Consequently, the belt **1504** itself gets increasingly dirty from the start to the finish of the cleaning process. The reverse process can also be useful in some alternative examples, such as where dust is collected by a belt for purposes of coating an object that travels along it. One example of such a coating process could be to coat glass sheets with powder, such that the glass sheets do not then stick to each other significantly when stacked. In this example, adjusting speed of roller rotation adjusts rate of powder pick up.

Several manufacturing techniques and methods can be used to make the electroadhesive surfaces such as the rollers including the electroadhesive pads described in the foregoing examples. One example method may include blow-molding a cylindrical plastic shape and then pad print (or roller print) electrodes on the outer surface using a conductive ink. Many conductive inks would be appropriate for this purpose as the electrodes carry high voltage and thus are tolerant of resistivity in the electrodes. This manufacturing process may facilitate implementation of "resistive electrodes" (e.g., 10^6-10^7 Ohms/sq) which inherently limit the amount of current that can be passed through the electrodes. Thus, the electroadhesive cleaning device may be safe to touch even if the dielectric coating protecting the electrodes is compromised. The electrodes printed on a roller may have a pattern such as straight stripes (e.g., as shown in FIG. **9**A), diagonal stripes (as shown in FIG. **9**B), a combination of the two patterns, or any other pattern. Type of pattern of the electrodes printed on the roller and controlling a speed of the roller can be used to cause time-varying as well as space-varying electric field to be presented to the foreign objects or debris on a surface to be cleaned before the debris is adhered to the electroadhesive surface. Such time-varying and space varying electric field may possibly improve debris pick up performance.

Once the electrodes are printed on the surface of the roller, the assembly (of the roller and the electrodes) may be covered with a dielectric coating of the appropriate resistivity. This coating could be made out of polyurethane, for example. The dielectric coating may be configured to be applied such that no air bubbles are in contact with the electrodes so as to avoid electric shorting and a decrease the performance of the electroadhesive roller.

The surface of the dielectric may also be designed and made to have low-friction. In one example, applying the dielectric coating may involve covering the roller with a close-fitting tube of polyurethane designed to heat-shrink tightly around the electroadhesive electrode surface. In another example, the coating process may involve dip-coating in liquid polyurethane and then curing the roller. These examples are for illustration only, and many other manufacturing examples are possible as well.

III. Example Operations

Although a wide variety of applications involving cleaning, dusting and otherwise manipulating particulate matter and foreign objects using electroadhesion can be envisioned, one basic method is provided here as an example. FIG. **16** is a flowchart of a method of physically cleaning debris from a surface, in accordance with an example embodiment. In particular, such a method can involve using or operating an active electroadhesive device or system, such as any of the various cleaning pad, track-based or conveyor belt based components, devices and systems described above. Although the blocks are illustrated in a sequential order, these blocks may in some instances be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation.

Beginning with a start step **1600**, an electroadhesive surface is brought close to or in contact with a surface to be cleaned at process step **1602**. In some examples, electroadhesion voltage may already be applied to electrodes before the electroadhesive surface is brought into contact with the surface to be cleaned. The electroadhesive surface is brought into contact with debris on the surface to be cleaned at step **1604**, which cause at least a portion of the debris on the surface to adhere to the electroadhesive surface at process step **1606**. At this step also, a voltage may be increased to increase electroadhesion force based on type and quantity of debris, for example. At a following optional process step **1608**, the surface area contact can be increased between the electroadhesive surface and each of the plurality of foreign objects as described with respect to FIGS. **4**B and **4**C. In some examples, a speed of rotation of the electroadhesive pad, roller, or belt can be increased so as to present a cleaner surface of the electroadhesive surface to the debris situated in front of the cleaning device. Increasing rotation speed, while keeping a constant travel speed of the cleaning device across the surface to be cleaned, may allow more debris to be picked up and deposited in a dust tray of the cleaning device, for example.

At a subsequent decision step **1610**, an inquiry is made as to whether or not the surface has been adequately cleaned. Detection of such status can be accomplished by way of one or more sensors, for example. In the event that the surface has not been adequately cleaned (i.e., a substantial amount of debris remains on the surface), then the method reverts to process step **1604**, where the electrostatic force can be reapplied or increased. In the event that the surface has been cleaned at step **1610**, then the method proceeds to process step **1612**, where the electroadhesive surface is moved away from the surface to be cleaned.

At the next process step **1614**, the electrostatic force can then be altered or modified, such as by adjusting the input voltage. Such altering can be a reduction or complete removal of the electrostatic force, or can even involve a reverse polarity pulse or application of repelling force. At the following process step **1616**, the debris can then be removed from the electroadhesive surface such that the electroadhesive surface can then be used to clean other surfaces. At a subsequent decision step **1618**, an inquiry is then made as to whether the cleaning is finished. If not, then the method continues to process step **1620**, where the electroadhesive surface can be repositioned with respect to the surface to be cleaned. The method then reverts to process step **1602**, upon which the entire method is repeated.

In the event that cleaning is finished at step **1618**, however, then the method proceeds to finish at and end step **1622**. Further steps not depicted can include, for example, sensing the type and/or amount of debris adhered to the electroadhesive surface, and providing added force or steps with respect to removing such items when they are sensed. Other steps can include providing and/or detecting an input with respect to particle sizes in the debris, as well as an actuation within a patterned electrode set that adjusts the size of particles that will be adhered. Other undisclosed process steps may also be included, as may be desired.

FIG. **17** is a flowchart of a method of active electroadhesive cleaning involving reusing an electroadhesive surface, in accordance with an example embodiment. The method can involve using or operating an active electroadhesive device or system, such as any of the various cleaning pad, track-based or conveyor belt based components, devices and systems described above. Although the blocks are illustrated in a sequential order, these blocks may in some instances be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation.

Beginning with a start step **1700**, a surface is cleaned at process step **1702**. Such a cleaning process can be identical or substantially similar to that which is set forth above in FIG. **16**, for example. At a subsequent process step **1704**, the level or amount of debris on the electroadhesive surface can be sensed. This can be accomplished by way of one or more sensors that measure the capacitance or resistance of the electroadhesive surface at one or more select locations. At a following decision step **1706**, an inquiry is made as to whether there is too much debris adhered to the electroadhesive surface. If not, then the method moves on to decision step **1708**, where another inquiry is made as to whether or not the cleaning process is finished. If so, then the method ends; however, if not, then the method reverts back to process step **1702** and begins anew.

In the event that there is too much debris detected at decision step **1706**, then the method proceeds to process step **1710**, where one or more reverse polarity pulses can be provided. At subsequent process step **1712**, debris is then repelled from the electroadhesive surface, such as a result from the reverse polarity pulse or pulses. At the following process step **1714**, the level amount of debris on the electroadhesive surface is again sensed. At a similar subsequent decision step **1716**, an inquiry is made as to whether there is still too much debris remaining on the electroadhesive surface. If not, then the method can proceed to decision step **1708**, with the process from that point already being provided above.

If it is determined at step **1716** that there is still too much debris on the electroadhesive surface, however, then a visible or audio alert or alarm is provided at process step **1718**, such as by a light or sound to the user. The electroadhesive surface can then be specially cleaned or even replaced at process step **1720**, upon which the method then ends at step **1722**.

FIG. **18** is a flowchart of a method of electroadhesive cleaning of a surface having debris thereon, in accordance with an example embodiment. The method can involve using or operating an active electroadhesive device or system, such as any of the various cleaning pad, track-based or conveyor belt based components, devices and systems described above. Although the blocks are illustrated in a sequential order, these blocks may in some instances be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based upon the desired implementation.

At block **1802**, the method includes a moving an electroadhesive surface over debris on a surface to be cleaned. An electroadhesive cleaning device such as any of the devices described in FIGS. **10**A-**10**I, **11**A-**11**C, **12**, **13**, and **14**A-**14**C may include an electroadhesive surface. The electroadhesive surface may include the surface of a roller as described in FIG. **11**A, or arrangements **1** and **2** in FIG. **12**, for example. In other examples, the surface may include the surface of an electroadhesive pad such as the electroadhesive pad **1206** in FIG. **12**. For instance, referring to FIG. **10**D, the electroadhesive cleaning device **1000** may be configured to move across the surface **1018** to be cleaned from debris **1022**.

At block **1804**, the method includes applying, by a power supply, a voltage to one or more electrodes located at or proximate to the electroadhesive surface, where the voltage causes at least a portion of the debris to adhere to the electroadhesive surface. The voltage can be applied by the power supply without an external input; however, in other examples, the voltage level may be based on an external input.

FIG. **19** is a block diagram illustrating providing a voltage by a power supply to electrodes based on a user-input, in accordance with an example embodiment. FIG. **19** depicts an input provided to an input component **1902**. As an example for illustration, the electroadhesive device may, for example, include a handle such as the handle **1004** shown in FIG. **4**D. The handle may include an input component such as a button, dial, knob, etc. A user may provide an input to the input component **1902** (e.g., a user pressing on a button or dialing a level of voltage). The input component module **1902** may provide a signal, based on the input, to a power supply **1904**. The power supply **1904** may, based on such signal, apply a voltage to electrode(s) **1906**. The electrode(s) **1906** may be coupled to the electroadhesive surface. As a result of the voltage applied thereto, the electrode(s) produce an electric field effective to produce electroadhesion forces causing debris on the surface to be cleaned to adhere to the electroadhesive surface. The voltage applied by the power supply **1904** can be controlled or modified (e.g., based on the input to the input component **1902**) such that a size of the debris to be picked up from the surface to be cleaned can be designated based on the level of voltage. An amount of debris on the surface to be cleaned may be indicated by the user. Based on the indicated amount, the speed of rotation of a roller or electroadhesive belt of the cleaning device can be modified to optimize pick up rate of the debris, for example.

Components of the block diagram in FIG. **19** may be configured to work in an interconnected fashion with each other and/or with other components coupled to respective systems. One or more of the described functions, components, or blocks of the block diagram in FIG. **19** may be divided up into additional functional or physical components, or combined into fewer functional or physical components. In some further examples, additional functional and/or physical components may be added to the blocks shown in FIG. **19**.

Returning to FIG. **18**, at block **1806**, the method includes, moving the electroadhesive surface, with the portion of the debris adhered thereto, away from the surface to be cleaned so as to remove the portion of the debris from the surface to be cleaned. The electroadhesive surface can include the surface of a roller and/or a belt, for example. As the electroadhesive cleaning device moves across the surface to be cleaned, the roller and/or belt rotate, while the debris is adhered thereto. The roller and/or belt rotate away, and thus remove the debris, from the surface being cleaned.

At block **1808**, the method includes, after the electroadhesive surface has moved away from the surface to be cleaned, removing the portion of the debris from the electroadhesive surface. The electroadhesive device may include a scraper and/or a brush, or any other cleaning component (e.g., a sponge) that may be configured to remove the portion of the debris attached to the electroadhesive surface. The scraper may, for example, be similar to the scraper **1114** shown in FIG. **11**B to the scraper **1032** shown in FIG. **10**F, and the brush may be similar to the brush **1034** depicted in FIG. **10**F. For instance, as the electroadhesive surface moves away from the surface to be cleaned, the removal component (e.g., scraper, brush, sponge, etc.) may be configured to remove the debris attached to the electroadhesive surface.

While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope and spirit being indicated by the following claims, along with the full scope of equivalents to which such claims are entitled. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

What is claimed is:

1. A device comprising:

at least one electroadhesive surface positioned at or proximate to one or more electrodes and configured to interact with debris on a surface to be cleaned, wherein the at least one electroadhesive surface is separate from, and configured to move relative to, the one or more electrodes; and

a power supply configured to apply an input voltage to the one or more electrodes to thereby cause at least a portion of the debris to adhere to the electroadhesive surface,

wherein the at least one electroadhesive surface is configured to move, with the portion of the debris adhered thereto, away from the surface to be cleaned so as to remove the portion of the debris from the surface to be cleaned.

2. The device of claim 1, wherein the at least one electroadhesive surface comprises a plurality of cilia to facilitate adhesion of the portion of the debris thereagainst.

3. The device of claim 1, wherein the at least one electroadhesive surface comprises a compliant surface configured to comply with a shape of the surface to be cleaned.

4. The device of claim 1, further comprising:

one or more rollers coupled to the at least one electroadhesive surface such that the at least one electroadhesive surface rotates, with the one or more rollers, away from the surface to be cleaned.

5. The device of claim 4, wherein at least one of the one or more rollers is configured to rotate in a same direction as a respective direction of motion of the device on the surface to be cleaned.

6. The device of claim 4, wherein at least one of the one or more rollers is configured to rotate in a direction opposite to a respective direction of motion of the device.

7. The device of claim 4, wherein the at least one electroadhesive surface is configured as a continuous track that moves with respect to a rotational motion of the one or more rollers.

8. The device of claim 4, further comprising:

a scraper proximate to the at least one electroadhesive surface coupled to the one or more rollers, wherein the scraper is configured to, as the one or more rollers rotate, remove the portion of the debris adhered against the at least one electroadhesive surface.

9. The device of claim 8, further comprising:

a tray configured to collect the portion of the debris removed by the scraper.

10. The device of claim 8, further comprising:

a spring coupled to the scraper and configured to push the scraper against the at least one electroadhesive surface.

11. The device of claim 1, wherein the one or more electrodes comprise a plurality of oppositely chargeable electrodes arranged in a given pattern.

12. The device of claim 11, wherein the pattern comprises an interdigitated pattern having a plurality of differing pitches.

13. The device of claim 12, wherein each of the plurality of differing pitches is configured to cause respective debris of a correspondingly different size to adhere to the at least one electroadhesive surface.

14. The device of claim 1, further comprising:

an ion charge sprayer positioned proximate to the at least one electroadhesive surface and configured to spray a plurality of ionic charges onto the debris, wherein electroadhesion of the portion of the debris results at least partially from the presence of the ionic charges sprayed on the debris.

15. The device of claim 14, wherein the one or more electrodes include exactly one electrode, wherein the exactly one electrode is configured to carry a charge of an opposite polarity from the plurality of ionic charges.

16. The device of claim 1, wherein the one or more electrodes are further configured to produce one or more reverse polarity pulses, wherein the one or more reverse polarity pulses result in respective repellant forces effective to repel the portion of the debris away from the electroadhesive surface.

17. The device of claim 1, further comprising:

one or more sensors coupled to the at least one electroadhesive surface and configured to detect an amount of debris adhered to the at least one electroadhesive surface.

18. A system comprising:

an electroadhesive surface positioned at or proximate to one or more electrodes and configured to interact with debris on a surface to be cleaned, wherein the electroadhesive surface is separate from, and configured to move relative to, the one or more electrodes; and

a power supply configured to apply an input voltage to the one or more electrodes to thereby cause at least a portion of the debris to adhere to the electroadhesive surface, wherein the electroadhesive surface is configured to move, with the portion of the debris adhered thereto, away from the surface to be cleaned so as to remove the portion of the debris from the surface to be cleaned; and

a removal component configured to facilitate removal of the portion of the debris adhered to the electroadhesive surface after the portion has been removed from the surface to be cleaned.

19. The system of claim 18, wherein a level of the input voltage corresponds to a size of debris to be removed from the surface to be cleaned.

20. The system of claim 18, further comprising:

one or more rollers coupled to the electroadhesive surface such that the electroadhesive surface rotates, with the one or more rollers, away from the surface to be cleaned.

21. A method comprising:

moving an electroadhesive surface over debris on a surface to be cleaned;

applying, by a power supply, a voltage to one or more electrodes located at or proximate to the electroadhesive surface, wherein the electroadhesive surface is separate from, and configured to move relative to, the one or more electrodes, wherein the voltage causes at least a portion of the debris to adhere to the electroadhesive surface;

moving the electroadhesive surface, with the portion of the debris adhered thereto, away from the surface to be cleaned so as to remove the portion of the debris from the surface to be cleaned; and

after the electroadhesive surface has moved away from the surface to be cleaned, removing the portion of the debris from the electroadhesive surface.

22. The method of claim 21, wherein the surface to be cleaned is a floor.

23. The method of claim 21, wherein the debris comprises particulate matter.

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